ECONOMIC GEOLOGY

VOL. XXXII JANUARY–FEBRUARY, 1937 No. 1

THE TIN ORES OF BANCA, BILLITON AND SINGKEP, MALAY ARCHIPELAGO.

NICOLAAS WING-EASTON.

PART I.

CONTENTS.

Introduction 1
Outline of geology
Summary of petrology and stratigraphy 5
Dr. Verbeek's opinion on the geology 8
Two granites of different age 9
Age of the intrusion; tin content; character of the sediments .. 11
The intrusion and its effect 13
The climate before, during, and after the intrusion 14
The ore deposits
Generalities 18
Disintegration deposits and their relation to veinlet zones 19
Examples of veinlet zones 19
Ores in the vein zones 22
Residual ores: 1. Koolit ore 24
2. Valley deposits (Kaksa beds) 26
The overburden of the kaksa. Mentjang ore 28
Exploration and exploitation of the kaksa: Kollong workings 29

To be concluded in following number.

INTRODUCTION.

Literature.—Very little has been written in English about the tin-ore occurrences in the Dutch part of the Malay Archipelago; this is also true of French and German. Moreover, the few existing articles are mostly inaccurate, or are entirely antiquated. A short review is to be found in Vol. I (1892) of "The Mineral Industry," and even this is based on official reports on Banca published some 15 or 20 years before that time, and written still

earlier. In the 30 volumes of this Journal only one paper gives some information, and that only on part of the subject.[1]

Obviously, the reason is that most of the articles on these deposits are written in Dutch, a language little known in English-speaking countries. As these tin-ore occurrences, however, present some interesting and unusual features, I thought it worth while to prepare this paper for the benefit of foreign readers.

A short account of the geology of the three islands is presented, but for conciseness they will be treated as if they formed an independent unit, though they are to some extent allied with the Riau group of islands and with the Malay Peninsula. Geological knowledge of the former is still deficient; tin is not altogether absent but, with the exception of Singkep, Karimon, and Koendoer, no workable quantities have so far been found. So much has been written in English about the latter, however, that it is not necessary to call attention in this paper to existing differences.

History and Geography.—The Sultan of Palembang in Sumatra, whose domain included the island of Banca in the 18th century, had the tin fields worked by Chinese laborers and, after the Government of the Netherlands Indies came into possession of the island (1817) this continued. Nothing of scientific value is known of these earlier workings. It was not until 1850 that a small party of mining engineers with some geological experience was sent there, and did good topographic and geologic mapping of the more important districts. In the tin areas, these maps are of such accuracy that they are used to this day. The result, however, was that succeeding engineers were so content with them that they only rarely troubled themselves with questions of more geological importance, which lay outside their proper field of activity, *i.e.*, the production of tin.

Following the example of Banca, the concessionaries of Billiton and Singkep also employed Chinese workmen. Although from the outset European officials looked after the workings

[1] Ferguson, H. G. and Bateman, A. M.: Econ. Geol., vol. 7, 1912.

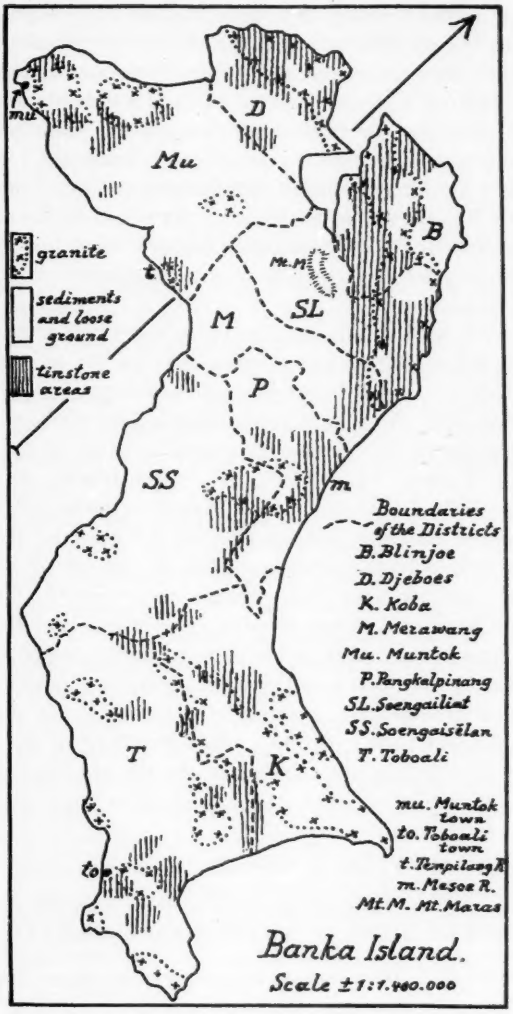


FIG. 1. Island of Banca.

here, the outcome of their experience was set forth in private reports which were then buried in the archives of the Companies. In Billiton, however, one of the former State mining engineers, Mr. C. de Groot, a man of great ability and a keen observer, was entrusted with the superintendency between the years 1866 and 1871. Sixteen years after his retirement he published a volume [2] in which a wealth of valuable data has been collected about the tin ore of Billiton, but as his ideas on the origin of the so-called "stream deposits" were contrary to the then prevailing opinions —though in after-years they proved to be correct—it attracted only little attention.

Meanwhile both islands were, as far as necessary, mapped geologically, and in the present century some of the officials have taken a greater interest in the scientific problems connected with the ore deposits. A brilliant and profusely illustrated account of the operations of the Billiton Company is to be found in its Memorial Volume 1852–1927. Many remarkable facts are further given in the writings of Dr. Rueb [3] on the secondary, and Dr. Groothoff [4] on the primary ores of Billiton, and Dr. Wilhelm [5] gave important particulars about the tin ore of Singkep. Numerous articles have been written about Banca, but they have contributed little towards solving the crucial problems.

Little interest was taken in the geology, and its supposed simplicity was in the main confirmed by a summary report of the professional geologist Dr. Verbeek [6] who visited Banca and Billiton in 1894 and 1895. In those times travelling in the islands was difficult and cumbersome outside the tin workings; his investigations, therefore, were mostly confined to these and to the coastal area.

[2] De Groot, C.: Herinneringen aan Blitong, 1887.

[3] Rueb, J.: (*a*) Ingenieur, 1915; (*b*) *Idem*, 1920.

[4] Groothoff, C. T.: (*a*) Verhandel. Geol. Mynbouwk. Gen., Geol. Sectie, vol. 1, p. 319; (*b*) *Idem*, vol. 3, p. 89; (*c*) De primaire tinertsafzettingen van Billiton. Dissertatie Delft, 1916.

[5] Wilhelm, C. H. J.: De tinertsafzettingen van het eiland Singkep. Dissertatie Delft, 1928.

[6] Verbeek, R. D. M.: Geologische beschryving van Banka en Billiton. Jaarboek v. h. Mynwezen in Ned. Ind., 1897.

The islands of Banca, Billiton, and Singkep[7] cover areas of about 12,000, 4300, and 800 sq. km. respectively. A considerable part lies beneath the 40 m. level, and here the solid rock is mostly concealed by a more or less thick sandy soil. The balance consists of hilly ground with summits rarely surpassing 500 m. altitude. The surrounding sea is shallow with a fairly uniform maximum depth not exceeding 40 m.

OUTLINE OF GEOLOGY.

Summary of Petrology and Stratigraphy.—The geology of the islands appears simple. A mica granite is the predominant plutonic rock; some granites also contain hornblende. The rock occupies a quarter or a fifth of the surface area, and its distribution is irregular. It is almost everywhere surrounded by sediments; and the islands and cliffs near the shore are, as a rule, also composed of them where the granite contours coincide with the coast line.

These sediments consist almost exclusively of alternating dominant sandstone, and clay shale. The sandstones are mostly fine-grained, pale colored, and poorly cemented; in the ore areas, however, the products of the oxidation of ferruginous minerals have stained them red and brown, hardening them at the same time. The common cement is clay either with or without a fine detritus of quartz, or it is silica, which forms a hard rock approaching quartzite. All varieties blend into one another. The clay shales are mostly pale colored and soft, but some are flinty. Some shales contain flakes of mica or graphite and resemble crystalline schists. True chert also occurs, and in southeast Billiton it was found to contain radiolaria.

The harder sediments commonly exhibit two or three systems of joints, which cause the rock to separate easily into parallelepipedons. The occurrence of these harder layers is not controlled by their proximity to or remoteness from the granite, and there is no mantle of metamorphic rocks around this granite.

Conglomerates are rare and their geological position is ob-

[7] In this paper the geographical names have all been written in Dutch orthography.

scure. Unconformities have not been observed. Microscopic examination revealed a granitic origin for all of the sediments; and the absence of lime in them demonstrates the acidic nature of the granite felspars.

With the exception of the radiolaria, the sediments seem to be entirely barren of fossils, so that their exact age cannot be ascertained. In the southwestern corner of Lingga island in the Riau group, badly preserved Daonella were collected, and from this discovery some writers infer a Mesozoic age for the sediments of all the islands between Billiton and Singapore. Older strata, however, are not *a priori* excluded.

Two other minor igneous rocks occur, namely: (*a*) dikes of rock of a diabasic character, in each of the three islands traversing the granite and, in part, crossing the sediments or bedded in them; (*b*) isolated blocks of quartz porphyry or liparite and its silicified tuffs in Banca and Billiton. In some islands of the Riau group, however, these rocks are more common.

The sediments almost invariably strike westerly or northwesterly. Dr. Verbeek measured mostly high angles of dip, in Billiton exclusively between 60° and 90°, in Banca some were as low as 20°. He got the impression that the sediments had been compressed into a few folds and, with some reservation, assigned them a considerable thickness.

My own experience in Billiton led to another conclusion; likewise, Dr. Adam, the geologist of the Billiton Joint Mining Co., came across many gentle and reverse dips indicating a more restricted thickness. Sandstone being the predominant and best exposed sediment, Dr. Verbeek generally used it for his measurements, but Dr. Adam noted that it commonly displays a prominent parting, parallel to the strike but dipping much steeper, and thus being more conspicuous than the bedding planes. High dips of the sediments are common in the tin areas.

In general the sediments form hills no higher than those of granite, but the highest eminences, both in Banca (Mt. Maras 700 m.) and in Billiton (Mt. Tadjem 510 m.), are built up of sediments. One would be inclined to ascribe this to faulting,

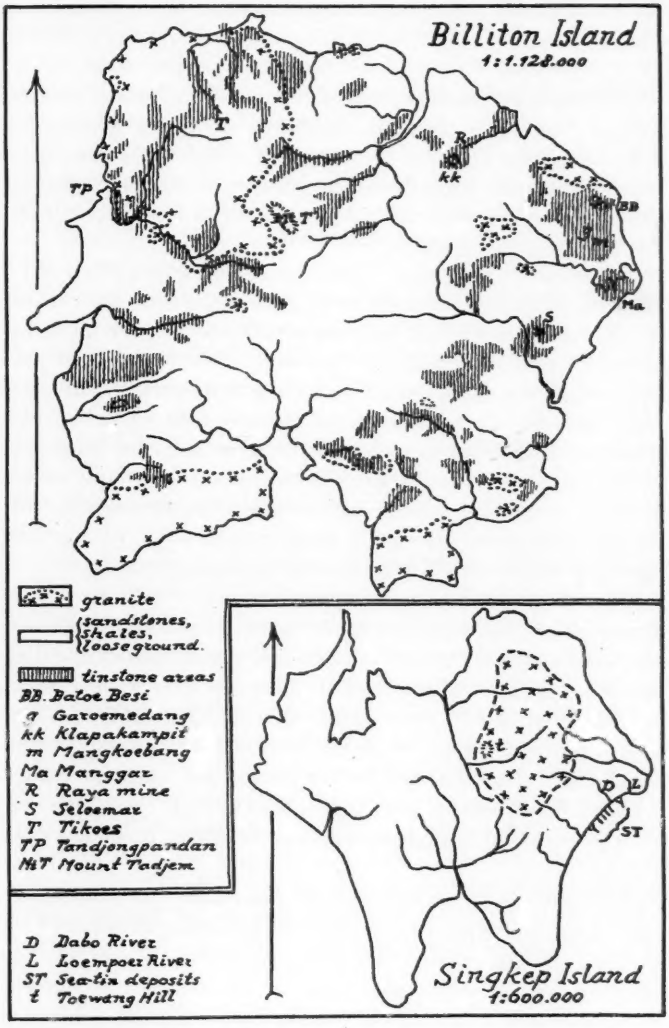


FIG. 2. Billiton and Singkep Islands.

as Dr. Verbeek did, though the evidence in favor of it is not strong.

Dr. Verbeek's Opinion on the Geology.—Dr. Verbeek observed several times (*a*) that the sediments bordering granite dip towards it, and (*b*) that they strike at a high angle toward the granite contact. From these observations he concluded that the sediments are the older and that their position was not controlled by the granite intrusion.

Moreover he found (1) in one district of Banca (Toboali) a network of granite veins traversing the clay shales, the enclosed fragments of which had been converted into hornfels; and (2) in the vicinity of Tandjong Pandan (Billiton) and in an islet near the Banca shore, hornfels at the granite contact. In these three localities the granite is the younger rock. On the other hand, no additional granite apophyses in sediment have been noted and, as Dr. Verbeek has admitted, along the granite contact there is a complete absence of metamorphic phenomena. Obviously these facts are strong arguments in favor of a greater age of at least a considerable part of the exposed granite.

The foregoing data suggest the existence of two granites of different age, and what follows makes this supposition still more probable. In every granite area of any size in each of the three islands, a portion of the rock is intensely altered to a white, soft mass, with smooth rounded outlines, whereas the balance, mostly rising to greater heights, is hard and fresh or only slightly weathered. This feature did not escape the attention of Dr. Verbeek but it was not then known that the soft condition is not merely superficial but extends in places to a depth of some tens of meters.

Summarizing the outcome of his researches, Dr. Verbeek advanced the following theory, *viz.* (*a*) probably no relics of the parental granite, which yielded the sediments, are exposed at present; (*b*) the sedimentary cover of the islands is presumably of Palæozoic age and has been compressed into steep folds; (*c*) during or shortly after this folding, granite was again intruded

and became exposed only after the sediments had been deeply eroded; (*d*) a difference in age among these younger granites cannot be established, although there is some variety in their petrographical character; (*e*) the intrusion is either of late Palæozoic or of post-Carboniferous age.[8]

Except for a change in consequence of the find of Daonella, the previous conclusions, as far as I know, still convey in substance the opinion of most geologists in this country. The present islands in the South China Sea are considered the remnants of a greater peneplain, and the loftier hills are monadnocks. The tin ore was deposited in the train of the intrusion; the "alluvial" ore represents the residue of the disintegrated vein fillings that had been left on the peneplain. My own ideas, which are only slightly in concurrence with the above, will be set forth throughout the text.

One of Dr. Verbeek's merits is that his descriptions are uncommonly objective, although he was well aware that some of them did not comply with his theory.

Two Granites of Different Age.—On the grounds already stated and on others discussed below, the present writer, during his stay in Billiton in 1920, arrived at the conviction that a great difference in age must exist between the two kinds of granite, but there was no opportunity to obtain conclusive evidence. It was still possible to attribute the intense alteration to a difference in mineralogical composition combined with hydrothermal effects.

Eight years later this evidence was supplied in the thesis of Dr. Wilhelm.[5] The top and the western slopes of Toemang hill in the island of Singkep proved rich in eluvial tin ore and were mined in the usual way. It was then found that the bedrock, a white, soft, "sectile" granite, *poor* in quartz, contained about 50 narrow parallel veins partly filled with quartz, cassiterite, some wolframite and tourmaline, and bordered by ore-bearing strips of greisen. It was decided to remove the entire hill by hydraulicking, but after some time this work had to be discontinued because there appeared a core of a different kind of granite hard,

[8] *Op. cit.*, p. 22.

evengrained, unweathered, and *rich* in quartz. The latter belonged to the kind that is predominant in the high hills along the eastern coast.

The boundary of the two kinds of granite, although not even, was sharply defined and showed no trace of a transition. The rocks on either side of the boundary being dissimilar in content of quartz, excludes the possibility that the soft granite is a kaolinized product of the hard. Moreover, the latter has a strong tendency towards exfoliating, whereas the former displays three sets of joints almost perpendicular to one another, which causes a parallelepipedic division of the rock, but does not extend beyond its boundary.

Another example is that of Boekit Besi in Billiton, described by Dr. Groothoff.[4a] On the flat elliptical top, 500 by 1000 m., some outcrops of a hard coarse granite are exposed, and at a depth of ten meters the granite of the lower slopes was as white, soft, and sectile as at the surface. The description of the rocks is not sufficiently detailed to decide whether there is an important difference in mineralogical composition, and the amount of quartz is not even mentioned. Two facts, however, have been emphasized by the author—(1) that the softness, most probably, is not due to tropical weathering, and (2) that the hard granite, although mostly fresh, becomes crumbly through weathering, *but does not show any trace of kaolinization.*[9]

Narrow tin-bearing veins, bordered by greisen, ramify through the hard as well as the soft granite, and Dr. Groothoff points out with justice that at the time when the veins originated, the crust must have been thin.

These examples lead to the inference that a later granitic magma invaded the existing rocks. One part of it was extruded in congealed condition to form the hills of the younger granite. A second and evidently small part escaped in liquid condition through fissures in the granite or through partings and fractures in the adjacent sediments, converting the latter into hornfels. A

[9] Dr. Verbeek also noticed such alteration (*op. cit.*, p. 29) in Muntok, Banca, where granite of higher hills is hard and weathers to a grit, but that of the low hills is soft and weathers to clay.

third part—the cores—remained hidden either in the old granite or in the overlying sediments.

This explains the scarcity of metamorphism at the granite contact: the younger granite is commonly surrounded by the older, and the latter existed before the sediments.

In my opinion, therefore, the exposures of *soft* granite represent portions of the primeval granite; the latter suffered disruption by the intrusion, and some of the blocks with the superincumbent sediments were elevated. The highest sedimentary ridges in Banca and Billiton probably also owe their elevation to such an upheaval which, however, did not expose the granitic basement.

In the earlier Banca reports attention was already drawn to the difference between hard and soft, exfoliating and jointed, steeply and gently sloping granite. Later, Mr. de Iongh [10] depicted the main features as follows: . . .

> The central body of Betong hill, Banca, consists of granite without a trace of ore or a single quartz vein. In the outliers towards the SE., however, the granite is distinctly jointed and contains many veins, some of appreciable width. I venture to suppose that the homogeneous firm framework of the hill, being highly resistant to weathering, was on the *very steep* E. and NE. slopes originally covered by a mantle of the cleft and jointed granite mentioned above, which here was destroyed by erosion.

For the rest there is a paucity of records on the subject, and it is to be regretted that so little attention was generally paid to the morphology of the islands and to the character and the mineralogical composition of its rocks.

Age of the Intrusion; Tin Content; Character of the Sediments.—Obviously the ores were formed as a sequel to the consolidation of the *younger* granite. Dr. Groothoff's description leaves no doubt that the greisen in the soft granite was formed during a period when the latter had already been kaolinized; this greisen is also much more brittle than that in the hard granite, although they originated at the same time.

The amount of tin ore in the parts of the younger granite which are above the general level, seems to be uniformly small, and no

[10] De Iongh, D.: Jaarboek Mynwezen Ned. Ind., 1884, II, p. 308.

deposits of any special importance have been found in it. It could not be otherwise, for the protruding cores had been to a certain extent solid before the mineralization set in. The bulk of the mineralizing substances escaped, passing through the adjacent sediments or through the older granite at the time when the intruded cores had been pressed up to a sufficient height.

Dr. Verbeek, who needed fresh material for his microscopic examination, sampled only the younger granites, and from 8 localities he sent specimens of the rock to Professor Cl. Winkler in Freiberg, Saxony, who analyzed them carefully.[11] Here the complete absence of cassiterite was established, and it is noteworthy that all the samples contained tin in some unknown compound, amounting from 0.0063 to 0.0288 per cent., which proved that part of the gases really did spread through the younger granite magma, but under conditions that did not permit them to interact and to form tinstone.

We do not know when the younger granite made its appearance; no decisive indications have been found in the islands to settle this matter. Taking into account (1) that liparite occurs fairly abundantly in some islands of the Riau group; (2) that fragments of coarse granite have been observed in a quartz porphyry or a related type of igneous rock in the island of Batam; (3) that boulders of quartz porphyry, presumably remnants of dikes, were found in Banca and Billiton, and tuffs of a similar material in Nangka island; (4) that in the small island of Telagepat nests of quartz, galena and sphalerite occur in silicified tuffs; I think it may be tentatively stated that the mineralization took place at about the same time that the liparite appeared, which rock abounds in the neighboring island of Sumatra, and is there of late-Pliocene age.

If this is correct, then the older granite must have been subject to erosion at least during the greater part of the Mesozoic and Palæogene periods. Meanwhile the sea gradually encroached on the land and the former continent became an archipelago.

The products of erosion and deflation settled partly on the land or in lakes, and partly on the continental shelves or in estuaries, so that radiolaria-bearing shales had an opportunity to form.

[11] Verbeek, R. D. M.: *Op. cit.*, pp. 116–132.

The present long Southeast-Asiatic tin belt must be considered as part of a formerly more extensive continental island, the eastern shore line of which is indefinite as yet. A small stretch of ground along the eastern coast of Sumatra proved to contain tin ore and may have belonged to this continent, but for the rest I infer that the geological history of the belt is independent of that of Sumatra, and has nothing to do with a geosyncline.

The Intrusion and its Effect.—The intruding batholith is considered to have been wave-like, with a tendency to move in a northeasterly (or reverse) direction. One of the functions of the waves was the compression of the granite and the sediments that stood in the way; hence the shearing and disruption of the old granite. The stress produced the thousands of minute fissures —the future carriers of the ore. In proportion to the absorption and stoping of the granite the compression and folding of the sediments set in. The folding and jointing was most intense near the granite, which acted as a buffer.

To explain the intruded cores and the extruded exposures of the younger granite, one would be inclined to agree with Falconer, who writes,[12] " that the upper surface of the batholith was probably highly irregular and the major irregularities on the surface of the plateau probably represent . . . fangs of the younger granite, which originally projected upward from the general surface of the batholith into the overlying rocks." If the extruded hills and the hidden cores represent " fangs," then these would be exits for the mineralizing solutions; they may have been connected with underlying pockets of magmatic residuals and have come into existence because of their strong upward pressure. The original surface of the waves may then have been rather regular (which is also more logical) and the upheaval *of the belt as a whole* fairly regular too. Only in its last stage the " fangs " originated and brought about an *additional* rise in some parts of the belt, *viz. the islands under review.* In a way these fangs may be compared with the cupolas in volcanic craters.

[12] Falconer, J. D.: Geol. Surv. Nigeria, Bull. no. 1, p. 11, 1921.

As regards the sediments, the final results were (1) that they lie in unchanged position *upon* the older granite, where they have been elevated with the latter; (2) that for the rest they dip more or less steeply *against* the older granite, unless folding and sliding caused complicated structures; (3) that their strike and dip are independent of the *younger* granite.

Upon the relief of strain that initiated the arrival of the magmatic residuals, the sediments in places split along the bedding planes, giving rise to fault fissures of medium size. Movements of those sediment-blocks were not uncommon later on, but they were of secondary importance.

The Climate Before, During, and After the Intrusion.—In preceding paragraphs it was pointed out (*a*) that the sediments existing in the islands embrace the erosion products of the Mesozoic, and probably also those of the Palæozoic. No diastrophism occurred during these eras, nor was there any volcanic activity. The sediments are noticeable for the paucity of fossil animal remains and the total absence of plant remains; (*b*) that the mineralization took place in the Pliocene, from which may be deduced that the intrusion itself was active in the Neogene; (*c*) that the older granite is always weathered and soft, not only at and near the surface but to a considerable depth; no matter whether this granite occurs within the tin-bearing areas or outside.

Palæometeorological problems are often among the most difficult to solve, because the features brought about by a preceding climate, may for the greater part have been obliterated by a succeeding one. It must, however, be understood

> that the greatest extremes of climate are not to be attributed to the abnormal development of any one factor, but to the cooperation of a number of different factors acting in the same direction. It seems probable that the dominant factors have always been "geographical," this term being given a wide meaning and including not only the distribution of land and sea and the systems of ocean currents, but also the general elevation of the land and other factors. Any change, geographical or astronomical, can become effective only through its action on the atmosphere.[13]

[13] From Brooks, C. E. P.: Climate through the Ages, London, 1926.

As regards the tin islands the solution is comparatively easy. It follows from (*a*) that the period of erosion was sufficiently long to make base-levelling thoroughly complete and, excluding the Palæozoic, the whole period of denudation was characterized by the " warm " climate which then reigned universally. In the first half of the said period, when the country was still mountainous and the sea-wind was forced to ascend, the latter expanded, cooled, and deposited its water content in the valleys. In the second half, however, in which the relief was greatly diminished,

> the country did not appreciably modify the planetary circulation. In summer, when the winds are generally weakest, continents in low latitudes are hot, and there being no mountain ranges to cause the ascent of air, the only rainfall would occur in sporadic thunderstorms and squalls.[13]

This rainfall was not heavy enough to counterbalance the evaporation; the rivers nearly dried up, and the little remaining water, occupying only part of the channels, meandered towards the sea. Such rivers did not deepen their valleys but broadened them by lateral planation. In this last stage of peneplanation, chemical weathering predominated over mechanical erosion. World wide fossils indicate that

> in the Eocene the tropical regions were warmer than they are at present, and with a mean annual temperature of 30° C. desert formation may occur with a rainfall as high as 1200 mm. a year, because the biological effectiveness of rainfall depends not only on the total fall, but much more on the amount which becomes available for plant life.[13]

There may have been some vegetation in the valleys and other suitable places in the islands but, broadly speaking, the country was bare, as the feeding substances had been removed from the superficial layers. Many months of warm and dry weather more than balanced the short and feeble rainy season, during which most of the water was absorbed by the decayed rock. There was no opportunity for the formation of coal.

Then, at the beginning of the Neogene, the intrusion occurred. The belt was elevated and a second period of erosion inaugurated. The elevation seems to have been comparatively slight, and probably was approximately balanced by the renewed denudation and

deflation, so that the general aspect of the country remained almost unchanged. The climate did not change either.

Apart from the fact that it did lower the groundwater level, the intrusion had a twofold effect. The direct effect was that large areas of continental shelves were exposed as new land, which restored the extension of the former continental island. The indirect effect was that this more extensive country, situated in a low latitude, tended to raise the temperature. Consequently, in the Neogene the islands were probably somewhat warmer and drier than in the Eocene; besides, the lowering of the groundwater level caused the alteration of the rock to extend deeper, so that a greater portion of the rain water could be easily absorbed. This added to the general aridity; and the vegetation was limited to the larger water courses, which received the drainage from a considerable area, and the intervening country was desert-like.

As far back as 1917,[14] I called attention to some signs of an arid climate in the Tertiary of Borneo and Sumatra, and the last sentence of this paper was: " The question put in the title had perhaps better be changed to: Had the East Indies, or at least a great part of them, a desert climate in the younger-Tertiary and presumably still earlier? " Also, Professor Volz was of the opinion that the Indian reed grass (alang alang), so widespread in the islands mentioned above, was a relic of an arid climate.[15]

In the foregoing it was pointed out that such a climate must really be assumed. More than 6 per cent. of the surface of Billiton is occupied by sandy plains unsuited to any culture, where the poor vegetation consists only of a dry hard grass and withered low shrubs. The grains of sand are mostly cemented by organic material to a brown colored mass (fo-sau-kak) impervious to liquids, and the stagnant water acquires a color somewhat resembling blood. It is likely that these plains are also relics of the former period of aridity.

If during this climatic period the year consisted of a long dry season and a short and feeble rainy one, the contrast with the present climate with its average of nine rainy months is very

[14] Tydschr. Kon. Ned. Aardr. Gen., 1917, pp. 680–695.

[15] Volz, W.: Gaea, 1909. Quoted in Tydschr. Aardr. Gen., 1917, p. 853.

striking. The intervening space of time was mainly occupied by the Quaternary Ice Age. Although the numerous papers issued on the climate of this age deal exclusively with the arctic and temperate zones, yet the large ice masses to the south and the north must inevitably have affected the tropical zones also. What I found on this subject is the following:

> The equatorial regions in general also had a greater rainfall than at present, though with local exceptions. Over the ocean the Trade winds, stronger in consequence of the greater temperature difference between the equatorial and polar regions, brought in more warm moist air than at present. The volume of air ascending in the equatorial belt of low pressure was therefore greater, and the rainfall in the Doldrums and over the eastern equatorial margins of the continents was heavier.[16]

Of course the transition from the warm and dry to the rainy period was not completed all at once. The mineralization of the islands occurred in the initial stage of this transitional period; during the formation of the ore beds the wetter climate had set in; and in a still later stage the overburden of the beds was laid down. The evidence for this was furnished in Singkep.[17]

In the soft bedrocks of the deep valleys in this island (either granite or sediment) fossil trunks and roots occur in places and have been exposed by hydraulicking. They stood upright, in places piercing the bedrock vertically to a depth of 3 m.; generally they did not project above the surface, but some of them protruded a little into the overlying ore deposit. The wood was recognized as belonging to kinds of Dipterocarpaceæ of Tertiary or, at least, Pleistocene age.

The following deductions may be made:

(1) The long roots bear evidence of the softness of the bottom during the growth; the vegetation was scarce and irregular.

(2) During the growth the valleys were empty and without permanently running water; the groundwater level lay deep.

(3) The trees died in the time when the ore bed was formed; they probably died through an excess of water; no wood remains have been found in the overburden.

[16] Brooks, C. E. P.: *Op. cit.*, p. 315.

[17] Wilhelm, C. H. J.: *Op. cit.*, pp. 96–101.

(4) The trunks and roots were preserved because an impermeable layer of clay formed over the ore; therefore, after the deposition of the latter, abundant water must have permanently flowed through the valleys.

These deductions corroborate what has been argued before, and their importance will become evident in the next section.

The deposits of bauxite found in some of the Riau group of islands, and the products of lateritization to be spoken of later on, likewise belong to the transitional period.

THE ORE DEPOSITS.

Generalities.—The tin ore in the islands occurs as: (*A*) Disintegration deposits or ore in loose ground, and loose ore beds. Together they constitute the so-called eluvial and alluvial—detrital, residual, secondary, streamed—ore. (*B*) Bed-rock deposits, or primary ore, *viz.* (1) in veinlets forming zones in granite, commonly accompanied by greisen; (2) in bedded and joint veinlets in sediments generally constituting networks; (3) in fracture and fault-fissure veins in sediments, not uncommonly assuming the character of lodes; (4) in quartz bodies in granite; (5) in greisen.

The origin of the primary ore is similar to that of other well-known countries, and is genetically related to granite. The pneumatolitic action produced small crystals of quartz and cassiterite, together with some wolframite, tourmaline and few sulphides as subordinate products (*B*.1 and *B*.2). Soon afterwards the gaseous phase gave way to the hydrothermal—colloidal—phase, during which iron sulphides predominated. The absence, or at least the scarcity, of most of the usual accessory minerals is characteristic of these ore deposits.

Pegmatite and aplite dikes are mentioned in the literature, but have attracted little attention. It is likely that the quartz bodies *B*.4 belong to the products of the pegmatitic stage.

Dr. Verbeek [18] described a rock from Koba, Banca, which shows hardly any trace of alteration, and the constituents of which are andesine and perthite with numerous flakes of hematite. Evi-

[18] *Op. cit.*, pp. 47 and 102.

dently this rock is an aplite;[19] it was found as boulders on granite in which it probably occurs as a dike. It contains neither ore nor quartz.

Further products of this stage may be the large loose-lying quartz crystals up to ½ m. in length, which occur in some areas.

A zonal arrangement of the ores, such as in Bolivia, does not exist in these islands. The sulphides of the base metals zinc, copper, and lead occur sparsely in some of the larger veins and, with an attendant deposition of arsenopyrite, in the greisen of Tikoes, Billiton. Pyrrhotite is a constituent of some lodes. A little gold is found in places. Topaz is confined to greisen occurrences, especially to the greisen of Tikoes.

The ores that belong to division (*A*), being economically the more important, will be treated first. They are, however, so intimately related to those of groups 1 and 2 of division (*B*) that a joint discussion will be inevitable.

Disintegration Deposits and their Relation to Veinlet Zones.

Examples of Veinlet Zones.— (1) Toemang hill, with its bundle of parallel narrow quartz-ore veins bordered by greisen and trending northwesterly in the soft granite has already been described. Between this granite and the southeast coast of the island Singkep, there is a broad zone of similar veins in and parallel to the sediments; this extends for at least 1500 m. along the sea bottom.

(2) On my visit to East-Billiton, I saw a series of parallel, narrow veinlets following the trend of the sandstone, and constituting a typical zone, on the floor of an open-cast mine in the Lemboeng valley. The filling consisted of minute quartz crystals in comb structure, commonly with interstitial cassiterite. There was no intergrowth of the two, so, evidently, the ore is the younger mineral. These veinlets were very brittle and readily disintegrated if gently pressed between the fingers. Commonly a narrow central channel separated the two rows of quartz crystals and there were also small spaces between the quartz individuals. I got the impression that the filling could not have been deposited by a liquid, but that it is the outcome of the interaction of gases.

[19] Rosenbusch, H.: Mikr. Phys. d. mass. Gesteine, vierte Aufl., 1907, I, p. 580.

The loose ore bed *in situ* was composed of exactly the same material, and the veinlets persist in depth for some distance.

On inquiry, I was informed that such occurrences were not at all rare in the eastern districts. Dr. Verbeek also mentions one on page 159 of his work. As the soft clayey bottom of an open-cast mine soon becomes dirty after the removal of the ore bed, and the veinlets are pale colored and unobtrusive, they have been generally overlooked.

(3) I was shown some large blocks built up of loosely coherent layers of the same brittle material as that of the veinlets (2), which had been found in the deep suction-dredge mine of Bengkoeang near Manggar, Billiton.[20] Probably this represents a local widening (example 5), or the coalescing of a number of veinlets. The cassiterite is partly well crystallized, partly subangular or in the form of grains. As this ore is undoubtedly in its original site, the rounded forms of the mineral cassiterite, found elsewhere, bear no evidence of transport, as has been suggested. I suppose that these peculiar, partly rounded forms are closely connected with the rapidity with which the individuals originated through the interaction of gases.

(4) Among the rubbish of the old hydraulic workings of Padang Rambai, southeast Billiton, I collected several fragments of veinstuff consisting of the same material mentioned in example 3, and also of sugar-quartz, which is easy to crush but more resistant than that of Bengkoeang, and abundantly intermingled and intergrown with tinstone.[20] Here the two minerals are about simultaneous in age.

(5) Dr. Verbeek mentions an ore body in the Mertoet hill, southeast Billiton, which occurs in perpendicular clay shales. At the surface its width was 4 m., but reached 10 to 12 m. at a depth of 6 m. and then abruptly tapered to a mere fissure. The shale itself was barren; the tinstone with friable quartz was concentrated in countless minute stringers filling the interstices of the bedding planes and joint fissures. It is emphasized that iron ores

[20] Photographs of these ores in Verh. Geol. Mynbk. Gen., Geol. Serie, vol. 8, p. 154, Pl. II and IV, 1925.

are lacking; neither are these found in the deposits of examples 2 to 4.

Two similar lens-shaped bodies, in soft granite, are described and illustrated by Dr. Wilhelm.[21]

(6) Mr. van Diest [22] saw many parallel quartz seams with tinstone in the granite bottom of old workings in Soengailiat, Banca.

(7) Mr. van Lohuizen,[23] described an ore deposit in the granite hills bordering Pandji river in Blinjoe, Banca. The soft rock is almost barren down to a depth of 12 m., where a payable bed was found. Borings and a prospecting shaft proved that tinstone was present over another 13 m. in veinlets (coarse ore), and in the adjacent greisen (fine ore), to an average amount of 0.12 per cent. The worked ore bed was approximately on the same level as the water of the river. When the overburden was being removed, the lighter tourmaline was found at a higher level than the cassiterite, and its quantity increased with depth. This indicates that the ore bed resulted from concentration caused by percolating rain water.

(8) In the higher ground skirting Pemali valley in Soengailiat, Banca, the soft granite was found to be "impregnated" with tinstone and was worked by ground sluicing to a depth of 11 m., yielding 0.26 per cent. of ore.[24] A considerable number of trial borings less than 4 m. deep were made to test the ore content of the stretch of granite lying along the boundary line. Ore proved to be present over an area of 10 km. in length to an average distance of 2 km. from that line; the average amount was only 0.002 per cent., but seemed to increase with depth. Probably here also the ore has been concentrated by the rainfall on a still lower level. This may have simulated an "impregnation," because the friable veinlets had been disrupted, leaving only a tenuous dissemination or ore.[25]

(9) Not long before the preceding discovery, a bed rock de-

[21] *Op. cit.*, pp. 30–31. See also Verbeek, *op. cit.*, p. 113.

[22] Van Diest, P.: Jaarboek Mynwezen Ned. Ind., 1872, II, p. 23.

[23] Van Lohuizen, H. J.: Jaarboek Mynwezen Ned. Ind., 1917, p. 204.

[24] Jaarverslag Banka-tinwinning, 1924/1925.

[25] No tinstone has been found as a primary constituent of the granite of the islands.

posit at Balai Bandoeng, near Pemali, attracted attention.[26] It consisted of a bundle of 55 veinlets in sediments within a space of 10 m., the veinlets ranging from a few mm. up to 6 cm. in thickness, and dipping 45° northeast. Upon testing the Pemali sediments on the other side of the granite margin, the outcome of 114 bore holes to a maximum depth of 124 m. indicated an area of 500 by 135 m. in which, from the surface to a depth of 75 m., the average amount of tinstone was estimated at 0.125 per cent. Even in the deepest boring the ore showed no tendency to decrease.[27] To verify this result, a shaft was sunk in the center of the area, but for economic reasons this work had to be discontinued after a depth of 54 m. had been reached, exactly at the point where the richer portion of the block began! Wherever the sediments dip steeply to the northeast, the veinlets follow the bedding and joint planes. In some places, however, the position of the sediments is much disturbed, but the real situation is not made sufficiently clear.

Systematic washing of the ground removed from the shaft revealed that the ore content per unit was twice that of the corresponding bore hole—a remarkable result.[28] Worthy of notice also is the similarity of the ore content of the granite and the sediments (See examples 7, 8 and 9). This was proved experimentally when the tin-bearing areas in sediments, drained by the Segentin river, Merawang, and those in granite, in the basin of the Liat river, Soengailiat, were worked. These areas are almost in line, the former a short distance to the south of the latter; both were extraordinarily rich and their ore originated from the same vein zone.

(10) Additional examples, that point to the occurrence of veinlet zones are to be found in the earlier reports on Banca, and in the volume on Billiton published by Mr. de Groot.

Ores in the Vein Zones.—The worked and workable areas in Billiton are shown on the map annexed to the Memorial Volume

[26] Jaarverslag Banka-tinwinning, 1923/1924.

[27] Twiss, W. J.: De Myningenieur, 1931, p. 71.

[28] In Banca and Billiton borings in the soft rock yield sampling results that are too low; actual output may exceed them by 50 to 100 per cent.

of the Company, and on p. 200 of Vol. I they are grouped into 27 tin zones generally corresponding with river basins. Nine of these zones are exclusively in granite; the trend of the others generally coincides with that of the sediments, which have yielded about 90 per cent. of the tin. It may here be remarked that although Billiton is rich in ore—the output of tin metal up to now having been 400,000 tons—only 2.85 per cent. of the surface belongs to the tin zones.

The total output of Banca is nearly one million tons and a good deal more than half of this has been supplied by the granite. Tin zones are not clearly marked here. In the chief centers of production Djeboes, Blinjoe, Soengailiat, Merawang, and Pangkalpinang, there appear to be three parallel zones trending northwesterly, but they do not extend far beyond the granite margins. I think it is safer to say that, generally speaking, the ore occurrences are confined to the granite and to a more or less broad strip of the adjacent sediments. As far as can be inferred from the maps, few deposits are parallel to the trend of the sediments. Evidently there is a striking difference with Billiton, which may be explained in the following way.

Where the sediments were still underlain by old granite, the mineralizers availed themselves of the shearing planes existing in the granite, or, to put it differently, the tin zone formed in the granite was projected upward into the sediments and retained its original dimensions; the deposition of the minerals however, took place along the bedding and joint planes, where conditions were most favorable. This may be called the Banca type of occurrence. It is known from experience that the extension of mineralization around the cores does not exceed 3 km.

On the other hand, where the old granite had almost entirely been absorbed or stoped by the magma, the substances entering the sediments selected such sedimentary zones as were folded, shattered and broken; thus, these zones coincide with the tin zones. A further consequence was that the less disturbed sediments were *not* invaded by the mineralizers. This may be called the Billiton type of occurrence, though apparently it is found also

in a few places in Banca. Small remnants of the old granite, which escaped stoping, have been enclosed between the sediments.

In some cases of the Billiton type, strong outbursts of gases through the magma must have taken place within a comparatively small space; and, if the overlying sediments were in a condition to let them pass, local accumulations of ore were formed with a roughly circular outline. There are several of these isolated occurrences, *e.g.,* Klapakampit, Seloemar, Nangka, but the most remarkable example is the phenominally rich country of Manggar hill and its outskirts, a surface of only 30 sq. km. which, up to 1925, yielded half of the output of Billiton.[29]

Although the vein zones may in places be traced for many kilometers, the simple veins behave differently. It is well-known that pneumatolytic deposits always show strong variations in behavior and constitution, and that equality in richness of a vein cannot be expected. The same reasoning holds good for a zone of veinlets. Thus, even where such a zone trends exactly in the direction of a valley, there may have resulted an alternation of rich and poor parts.

The sites of the veinlet zones were independent of the particular conditions of the surface. Therefore, an ancient valley might not be traversed by them, whereas the high ground on the valley banks is very rich; or, only the left or the right part of a valley is ore-bearing; or the ore is confined to a higher part of the bottom and is absent in an adjacent lower part. It is difficult to explain these and similar occurrences on the basis of the "stream theory", which stipulates that the ore has been carried down by the water of the river. On the other hand, they support the supposition that the ore in the valleys originated approximately at the same spot where it is now. It is to Mr. C. de Groot's credit that he was the first and for a long time the only one to realize how the "secondary" ore had originated.[30]

Residual Ores: Koolit Ore.—The common rule is that the narrowest veins are also the purest, having few, if any, injurious minerals, especially sulphides. The latter generally occur in the

[29] Gedenkboek Billiton I, p. 103.

[30] *Op. cit.,* p. 227.

broader veins which, although not altogether absent in granite, are more common in the sediments.

The first miners, the Malay natives from Palembang, worked only the ore that occurs just below the surface, in the decomposed eluvium. This subsoil, 2 to 30 dm. thick, they called a *koolit* (Malay for skin, crust, exterior) and this word has persisted.

Such koolits occupied a considerable part of the rolling or level country between the valleys, and the winning of the tinstone by ground sluicing was easy and cheap. In later days the Chinese adopted the same method. If water under natural pressure was not available in sufficient quantity, the deposit remained idle. The Chinese method was crude and uneconomical; only the richest portions were removed and the loss of ore in the tailings was heavy, in some instances probably amounting to 50 per cent.

The ore in the koolits is rarely distributed uniformly. Commonly two or three ill-defined slices, more or less different in color or character, can be distinguished, the upper slice being poorest, the undermost richest. It is believed that this concentration of ore is not due to gravitation only, but that the rainfall also had a share in it (See example 7); lateral shifting of the ore was unimportant.

In a later period, some koolits close to the sea have been exposed to the influence of the surf, changing the original situation, though not always in the same way.

Although the bottom of a koolit in granite is never quite smooth, rich ones in sediments are commonly full of mounds, hollows, furrows, and notches. The latter represent the broken-up veins, and above them the ore had accumulated. A striking example was mentioned by Mr. D. de Iongh.[31] In one koolit, a rich nest of ore, 4 m. deep, worked in 1873 by a small Chinese company, yielded 8500 kg. of metallic tin per head.

The koolits on the East-Billiton sediments are notable for the many large lumps of tinstone they have yielded, among which were some that weighed more than 1000 kg.[32] Some of them

[31] De Iongh, D.: Jaarboek Mynwezen Ned. Ind., 1884, II, p. 314.

[32] Verbeek, R. D. M.: *Op. cit.*, p. 136—The famous Gormanstown tinstone nugget, from Tasmania weighs 19 cwt., of which ¾ is tinstone (Jones, Tinfields of the World, p. 364).

possessed two parallel faces, indicating their origin from veins, others were irregularly shaped and mostly rounded but not abraded like boulders.

Lateritization produced patches of staniferous gritty ironstone, or, in places, a hard and tough cap of a similar substance, called tet-si-koi by the Chinese, which made mining a difficult task.

Fairly extensive layers of hard ferruginous pebbles and boulders, mostly covered by loose sandy soil, are found in several sedimentary areas, mostly in Billiton, and have been called *kreekil* (Malay for gravel). Although specimens of these boulders may have a tin-ore content of 40 per cent. and upward, the average content of the kreekil is rather small and, owing to dressing difficulties, the material is of no great economic importance. Careful testing of some areas showed that the kreekil is closely connected with zones of pyrite-bearing tin veins, and that the ore content decreases rapidly as the distance from these veins increases. Evidently the kreekil is a colloform deposition of hydrated iron oxides, more or less mixed up with crystals and detritus of the rest of the vein filling. In the outer shell of the pebbles, however, part of the iron compounds have been converted into hematite and magnetite.

Where the koolit was thick and its richest portion lay deep, the natives did not strip the overburden, but they sank narrow shafts and extracted the payground therefrom. Numerous traces of these workings were still visible when the first Europeans arrived in Banca, and they called them "Palembang pits." A similar method was applied later in Singkep to work the deep leads.

Residual Ores: Valley Deposits (*Kaksa Beds*).—Many valleys in the islands show a remarkable feature. Approaching the valley side, the traveller descends a short and hardly perceptible slope, after which he reaches a saggy soil in places several hundreds of meters wide and covered with a dense jungle, in the midst of which (in the dry season) a narrow brooklet meanders sluggishly in a bed of dark swamp clay. There is nothing to make him suspect that it is a false bottom upon which he stands,

and that several meters of earthy and gritty wash separate him from the actual floor. When he has been told this, his first conclusion is that such a broad and deep basin could never have been excavated by this rivulet.

The filling of the valley ranges in thickness from 2 to 20 m., exceptionally to 25 m., and averages from 6 to 8 m. It is everywhere of the same composition, *viz.* white or pale colored, and in places dark clay, with fine and coarse sand; the two components are rarely pure but are generally admixed.

If the valley contains ore, then the main ore bed, generally also the only one, invariably lies lowest, directly on the bedrock, which is always strongly weathered, whether it is granitic or sedimentary rock.

This main ore bed was called *kaksa* by the Chinese, a term which is now commonly used (The Malay call it *karang*). It is remarkable that no distinct traces of former river gravel have been found between the kaksa and the bedrock. These kaksa beds may be in a way compared with the " deep leads " in other countries.

The bottoms of the valley deposits are likewise rarely even; the early Banca reports contain several instances of very hummocky bottoms; others have counter slopes or the depth across the valley is unequal. The ore, as a rule, is not affected by this, although small, deep clefts may be enormously rich because they are broken-up veins.

The kaksa bed itself consists of from 80 to 95 per cent. of acute or subangular small crystals and fragments of quartz; the balance is composed of from 2 to 5, rarely as much as 10 per cent. of tinstone, white clay, veinstuff, tourmaline and other minerals. Accidental and more local admixtures are rounded lumps of a substance chemically resembling either kaolin or bauxite; big translucent quartz crystals up to some decimeters in length; fossil fruits; logs of wood; clusters of resin; and, exclusively in some valleys in Billiton, the peculiar vitriform bodies known as Billitonites, belonging to the tectites.

Mr. Hövig [33] states that the tin ore in the Banca kaksa is commonly patchy or streaky, but from top to bottom is fairly equally

[33] Hövig, P.: Verh. Geol. Mynbk. Gen., Geol. Serie, vol. 7, p. 4, 1923.

admixed with quartz; there is no increase of tenor in the lower portions of the bed.

The kaksa as a whole is an unsorted and incoherent mass but, as in the koolit, lumps of hard ironstone or caps of tet-si-koi are found in places.

From the foregoing it may be concluded that the kaksa must have lain bare for some time.

Small fragments of hard sandstone, quartzite, or chert are of common occurrence in the kaksa resting on a sedimentary bed-rock; boulders or subangular blocks of the local rocks, however, are lacking except for a few localities near the sea as I noted in East-Billiton, and as has been recorded of Banca.[34]

Comparatively speaking, it rarely happens that the kaksa extends in a layer of fairly equal thickness over the entire floor. Generally there is an alternation of richer and poorer streaks, which ramify and unite again, or the ore covers only part of the bottom. In the midst of poor areas extraordinarily rich patches and pockets may appear and the reverse also holds good. Neither is there an equal distribution of ore along the length of the valley; richer deposits alternate with poorer, and with almost sterile parts. Evidently this must occur where vein zones traverse the valley obliquely.

The thickness of the kaksa bed generally ranges between some cm. and 6 dm., but thicker beds up to more than one meter are not altogether rare. Exceptional cases are recorded of Singkep (2 m.) and Billiton (3 m.). It is, however, to be noted that thickness and richness of a kaksa bed do not necessarily go together.

The Overburden of the Kaksa.—Mentjang Ore.—The overburden of the kaksa is stratiform; the layers are of various extension, commonly more or less lens-shaped, and generally nearly horizontal. Two layers may rarely grade into one another, but as a rule their boundary lines are fairly well defined, and in cross-sections the boundary of the white clay is often visible over the

[34] De Iongh, D.: Jaarboek Mynwezen Ned. Ind., 1885, II, p. 176.

full width of the valley. This cannot be a normal stream deposit.

As the order of deposition of the material is not everywhere the same and varies even in the same valley, the material itself must be of local origin. Mr. van Diest, who spent many years in Banca and had a profound knowledge of the tin workings, wrote:

> Different layers occur on top of the ore bed. Sometimes it is covered by a bed of coarse sand overlaid by fine and loose sand; a seam of white, brown, or black clay may alternate with it. Moreover thick layers of sand are found mixed up more or less with clay and the reverse also occurs. Commonly most of the sand lies immediately on top of the ore.

Dr. Verbeek described 43 cross-sections of the overburden, among which 22 have underlying coarse sand, 11 have underlying clay, 4 have sand only, and 6 sand and clay mixed. Most of these sections refer to Billiton. The alluvium of the Dabo valley in Singkep shows a similar composition.

The overburden is not wholly devoid of ore but in the main is very poor and of no economic value. Here and there a second ore bed occurs, and exceptionally a third one. Such an intercalated ore deposit is called *mentjang* by the Chinese, and it is stated that in habit and composition it always differs from the kaksa, so that the two cannot have had a common origin. Though little attention has been paid to such cases, it is quite certain that special conditions have played a part in the origin of the mentjang ore. This will be discussed below.

Exploration and Exploitation of the Kaksa.—Kollong Workings.—Because the kaksa is concealed, it was discovered only after it had been proven that the koolit ore on the valley banks continued into the shallow valleys of the upper courses of some rivers. From the foregoing, however, it may be inferred that, on economic grounds, it was necessary first to test the value of the kaksa. For this purpose one of the first mining engineers, Mr. J. E. Akkeringa, invented the ingenious instrument which, modified and improved in some details, is still extensively used under the name of Banca Drill or Billiton Drill in the Nether-

lands East Indies, the Guianas and Siberia, and under the name of Empire Drill it has also been used in America. From the beginning this instrument should have been called "Akkeringa Drill" in honor of the inventor who probably contributed most to the evolution of ore winning in the tin islands. It testifies to his genius that this drill, though designed for shallow work, proved equally useful as the work became deeper and the risks of the undertakings increased.[35]

After a preliminary testing, such parts as are promising are prospected minutely and the payable sections mapped.

To yield the same profits, the kaksa, for evident reasons, must be much richer than the koolit. All deposits being different in character, each deposit must stand on its own merits, and average figures are of little value. But if, for instance, the volume of a koolit is computed from the grass roots to the solid rock, and that of a kaksa section from the water level to the bedrock, then, *per unit of volume,* the ore content in the kaksa of that section ought to be at least ten times greater than that of the koolit, with the proviso that neither the koolit nor the overburden of the kaksa has an exceptional thickness.[36]

After a section had been indicated, a dam was built across the valley at the extreme upstream end of the property, and the storage reservoir thus formed was connected by an adjustable ditch with the valley at the downstream end. The water stored was used to sluice down the overburden as much as possible; the remainder and the kaksa were carried to the surface by hand labor. Such an open-cast work was termed *kollong* (= deep) by the Chinese. In course of time this kind of work has been gradually superseded by mechanical devices.

RIJSWIJK, HOLLAND,
Dec. 1936.

To be concluded in next number.

[35] For description and illustrations of this drill, see C. C. Longridge, Hydraulic Mining p. 31, London, 1910.

[36] Gedenkboek Billiton I, p. 144.

THE PARAGENESIS OF PYRRHOTITE.

G. M. SCHWARTZ.

INTRODUCTION.

In a discussion of ore minerals with the writer, Professor W. H. Emmons expressed the opinion that pyrrhotite was one of the most significant minerals found in ores. It not only is considered a definite evidence of high temperature of formation, but its ease of alteration under oxidizing conditions makes it, and the acid solutions derived from it, especially active.

The above statement on the significance of pyrrhotite has frequently recurred to the writer on observing pyrrhotite in polished surfaces of ores, especially where pyrite is earlier than pyrrhotite in spite of the indication of high temperature by the latter. Other ores show pyrrhotite replaced by pyrite or marcasite. This leads to the question as to what is the real relationship of pyrrhotite to other minerals, especially to pyrite and marcasite.

The occurrence of pyrrhotite as an important mineral in ores is mainly limited to deposits classified as magmatic segregation, contact metamorphic and veins of the deep zone by Emmons, and as magmatic, pyrometasomatic and hypothermal by Lindgren.

It is significant that the great amount of detailed microscopic work on polished ores since 1910 has verified the restriction of pyrrhotite to these deposits. In thousands of specimens from other types of deposits the writer has rarely seen even microscopic occurrences of pyrrhotite, and a review of the literature suggests that this is the experience of other investigators. Although pyrrhotite is found in several gold deposits classified as mesothermal, it is mostly small in amount, and the deposits are probably on the border line between the hypothermal and mezothermal zones.

The data presented here are a result of a restudy of several hundred polished pyrrhotite specimens in the laboratories of the Department of Geology at the University of Minnesota, and a

review of over one hundred descriptions in the literature on pyrrhotite, especially where the relationships have been observed with the reflecting microscope. Suites of ores were examined from the Homestake Mine, South Dakota; Parry Sound, Ontario; Fierro, New Mexico; Ducktown, Tennessee; Sullivan Mine, British Columbia; Sudbury, Ontario; Noranda and Abana Mines, Quebec; Sherritt-Gordon and Flin Flon Mines, Manitoba; Cuyuna Range, Minnesota; and Potosi Mine, Chihuahua, Mexico. One or more specimens were examined from the Atikokan Range, Ontario; Cooke City, Montana; Little Bob Mine, Georgia; Cook County, Minnesota; and many others.

The work was aided by a grant from the Research Funds of the Graduate School of the University of Minnesota, which is gratefully acknowledged.

REVIEW OF PREVIOUS WORK.

Pyrrhotite as a distinct mineral was recognized at least as far back as 1747, as shown by the references listed by Dana. Because of its peculiar composition it has been repeatedly analyzed although many of the analyses are not acceptable because of impurities which were not determinable until the introduction of the study of polished surfaces. An extensive compilation of analyses is given by Heuglein,[1] with an exhaustive summary of many aspects of the occurrence of the mineral. For present purposes the most important information is derived from studies made by modern chemical and microscopic methods, especially the physical-chemical studies made by the Geophysical Laboratory, and detailed microscopic studies by various workers. Some of the earlier observations of pseudomorphs both of and after pyrrhotite are also applicable to the problems considered in this paper. With the exception of the descriptions in German in Doelter's Handbuch and in Schneiderhöhn-Ramdohr, Lehrbuch der Erzmikroskopie, there does not seem to be any general treatment of the paragenesis of the mineral. Discussion of the physical-chemical studies is presented later in the light of the actual occur-

[1] In Doelter, C.: Handbuch der Mineralogie, vol. 4, pt. 1, pp. 499–506, 1926.

rence of the mineral, as shown by microscopic studies. Newhouse [1a] has presented valuable tabulations of pyrrhotite bearing deposits of Nova Scotia in a paper published since the manuscript of this paper was completed.

Associated Minerals.

Pyrite.—A noteworthy fact is the common association of pyrrhotite with pyrite and this puzzling occurrence, more than any other, led to the present study. Since pyrrhotite is a typical high temperature sulphide, generally occurring in magmatic deposits, and pyrite is less common in close association with magmatic processes but is found throughout the range of sulphide deposits, one might logically expect it to form later than pyrrhotite when the two are associated. On the contrary pyrite is usually earlier in origin than pyrrhotite.

The tabulations of associations (Figs. 1, 2) show that pyrite occurs with pyrrhotite in 74 of the 86 occurrences listed. Of 56 districts, in which the order of formation of the minerals is known, pyrite precedes pyrrhotite in 35 cases, follows pyrrhotite in 8 and is not recorded in 14.

It is impractical to review all of the examples of pyrite described as earlier than pyrrhotite, but perhaps a few typical cases will be of value.

Ries and Somers [2] described pyrite from Röros, Norway, as fractured and filled with pyrrhotite. Jewell [3] found pyrite cut by pyrrhotite veins at Hyder, Alaska. At Chitina [4] pyrite is shattered and followed by pyrrhotite. At Shakan [5] pyrite appears as relics in pyrrhotite. At Ducktown, Tennessee, Gilbert [6] describes

[1a] Newhouse, W. H.: A zonal gold mineralization in Nova Scotia. ECON. GEOL., vol. 31, p 811, 1936.

[2] Ries, H., and Somers, R. E.: The pyritic deposits near Röros, Norway. Am. Inst. Min. Eng. Trans., vol. 58, pp. 244–264, 1918.

[3] Jewell, W. B.: Mineral deposits of the Hyder district, southeastern Alaska. ECON. GEOL., vol. 22, pp. 494–517, 1927.

[4] Ross, C. P.: Mineral deposits near the West Ford of the Chitina River, Alaska. U. S. Geol. Surv. Bull. 849 E.

[5] Buddington, A. F.: Molybdenite deposit at Shakan, Alaska. ECON. GEOL., vol. 25, pp. 192–200, 1930.

[6] Gilbert, G.: Oxidation and enrichment at Ducktown, Tennessee. Am. Inst. Min. Met. Eng. Trans., vol. 70, pp. 978–1023, 1924.

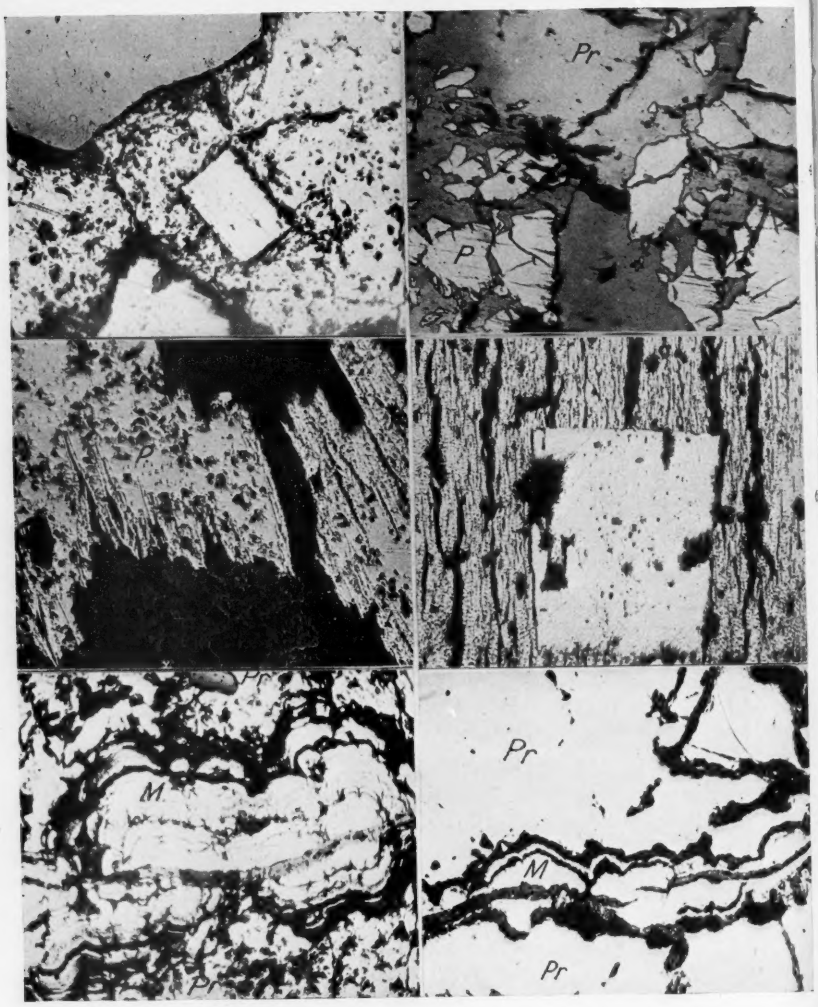
DISTRICT	MINERALS									DISTRICT	MINERALS								
	PYRITE	MARCASITE	CHALCOPYRITE	SPHALERITE	MAGNETITE	GALENA	CUBANITE	PENTLANDITE	ARSENOPYRITE		PYRITE	MARCASITE	CHALCOPYRITE	SPHALERITE	MAGNETITE	GALENA	CUBANITE	PENTLANDITE	ARSENOPYRITE
Aldermac, M, Que.	●		●							Kokomo, Colo.	●	●		●		●			
Amulet M, Que.	●		●	●		●	●		●	Kowkash-Ogoki, Can.	●		●	●		●			
Angangueo, Mex.	●	●	●	●		●			●	Knox Co., Maine	●		●		●				
Ashley M, Ont.	●		●	●	●	●				LaTouche Is, Alas.	●		●	●					
Atikokan, Ont.	●		●		●					Litchfield, Conn.			●		●			●	
Atlin, B. Columbia	●	●		●		●			●	Little Long Lac, Ont.	●		●	●	●				●
Beatson, Alaska	●		●	●		●	●			Llallagua, Bolivia	●	●							
Bersbo, Swed.	●		●	●	●					Marble Bay, Alas.	●		●	●	●	●		●	
Boliden, Swed.	●		●	●	●	●			●	Michipicoten, Ont.	●	●	●						
Bourlemaque, Que.	●		●							Miggiandone, It.	●	●				●		●	●
Bridge River, B.C.	●		●	●		●			●	Morro Velho, Braz.	●		●						●
Broken Hill, Aus.	●		●	●	●	●	●		●	Mt Bischoff, Alas.	●	●	●	●		●			●
Bushveldt, S. Af.		●	●				●	●		North Pines, Ont.	●			●	●	●			
Cobar, Australia	●	●	●	●	●	●				Oiseau River, Man.	●	●	●	●	●		●	●	●
Cuyuna, Minn.	●	●								Orange Co., Vt.	●			●	●		●	●	
Chicagof, Alaska			●						●	Ore Knob, N.C.	●			●	●	●	●	●	
Cape Smith, Can.	●		●							Panamint, Cal.	●	●	●						
Chulitna, Alaska	●		●	●		●			●	Parry Sound, Ont.	●			●	●	●		●	
Cook Co., Minn.	●		●		●			●		Pecos, New Mex.	●			●	●				
Dahlonega, Ga.	●		●	●	●	●			●	Potosi Claim, Mex.	●			●	●	●	●		●
Dallas, Georgia	●		●	●						Prince William Sd.	●			●	●		●	●	●
Ducktown, Tenn.	●	●	●	●	●	●				Robb-Montbray, Q.	●			●	●				
East Hecla, Ida.	●		●	●		●				Roros, Norway	●			●	●	●	●		
Ehrenfriedendorf	●		●	●	●				●	Rossland, B.C.	●	●	●	●	●	●			●
Ely, Vermont			●	●						Sachsischen, Ger.	●			●		●			
Ely, Nevada	●		●	●	●	●				Shakan, Alaska	●			●	●				
Falun, Sweden	●		●		●					Shebandowan, Ont.	●			●		●			
Fierro, New Mex.	●		●	●	●		●			Sherrith-Gordon, Man.				●	●				
Flin Flon, Man.	●		●	●	●	●	●		●	Singhbum, India	●			●		●		●	
Flaad Mine, Nor.			●						●	Spring Hill, Mont.	●								●
Fontana, N.C.	●		●	●	●	●				Stobie Mine, Ont.				●		●		●	
Gossan Lead, Va.	●		●	●		●			●	Sudbury, Ontario	●			●		●		●	●
Gordonsville, Va	●		●	●		●				Tasmania Cl, Alas.		●	●					●	
Harz Mts, German.	●		●		●			●		Torrington, Conn.				●		●			●
Hedley, Br. Col.	●		●	●					●	Transvaal, S. Af.	●	●	●			●		●	
Hitachi, Japan	●		●	●	●	●				Tyrol, Austria	●			●	●		●		
Horne M, Quebec	●		●	●	●	●				Vancouver, B.C.	●			●		●			
Homestake M, S.D.	●		●						●	Victoria, Austral.	●			●	●				●
Hyder, Alaska	●		●	●		●	●			Waite-Ackerman, Q.				●	●				
Insizwa, So. Af.			●						●	Wayhutta, N.C.	●			●	●		●		
Julian, Calif.	●								●	Wicklow, Great Br.	●			●					●
Juneau, Alaska	●		●	●		●				Yacobi Is, Alaska		●	●					●	
Kaveltorp, Swed.	●	●	●	●	●	●	●		●	Zimapan, Mexico	●		●	●		●			●

Figure 1.—Tabulation of the most common minerals associated with pyrrhotite.

DISTRICT	ORDER												REFERENCE
Aldermac Mine, Quebec	Py	Pr	Cp										Trans. Can. Inst. M&M. 31, 57-82
Amulet Mine, Quebec	Py	Pr	Cp	S									Can. Geol. Sum. Rep., 1933 D, 83
Angangueo, Mexico	Py	A	Pr	G	S	T	Cp	Mi					Ec. Geol. 10, 330-347
Atlin, British Columbia	A	Pr	S	G	Te	Py	Cp	Cc	M				Eng. & Min. Jour. 125, 495-7
Atikokan, Ontario	M	Pr	Py	Cp									Ont. Dept. Mines, 38th An. Rep. 1-58
Beatson Mine, Alaska	Py	S	Pr	Cp	Cu								Ec. Geol. 19, 336-64
Bersbo, Sweden	M	Py	Pr	S	Cp								Lindgren Mineral Dep., 839
Big Bonanza Mine, Alaska	Py	S	Pr	Cp									Ec. Geol. 9, 153-74
Bridge River, British Col.	A	Pr	Py	B	Cp	S	G	Au					Can. M. & M. Bull. 268, 405
Bushveldt, South Africa	Pr	Pe	Cu	Cp	Cu								Chemie der Erde 4, 252-86
Chicagof Island, Alaska	Pr	Pe	Cp	Pe									Ec. Geol. 19, 369-76
Chulitna R., Alaska	A	Py	Pr	S	G	Cp							U.S.G.S. Bull. 849 E.
Cowboy Mine, Oregon	Co	S	Cp	Cu	Pr	S							Ec. Geol. 27, 577-613
Cuyuna Range, Minn.	Pr	Py	M										Ec. Geol. 19, 466-72
Dallas, Georgia	Py	Pr	S	Cp									G.M. Schwartz, Unpublished
East Hecla Mine, Idaho	Py	Pr	Cp	Te	S	G							Ec. Geol. 20, 573-86
Fierro, New Mexico	M	Py	Pr	Cp	Cu	S							Ec. Geol. 18, 270-77
Flin Flon, Manitoba	M	Py	A	Pr	S	Cp	Cu	G	Au	T			Can. Inst. M&M. 38, 261-86
Fontana, North Carolina	M	Py	Pr	S	Cp	Cc	Mr						U.S.G.S. Prof. Paper 179, 73
Gordonsville, Virginia	Py	S	Pr	Cp									Ec. Geol. 9, 153-74
Gossan Lead, Virginia	Py	Pr	S	Cp									U.S.G.S. Prof. Paper 179
Harzburg, Germany	M	Pr	Pe	Cp									Centralb. f. Min. 1926, 322-32
Hitachi, Japan	Py	S	Cp	Pr									Ec. Geol. 19, 434
Homestake Mine, So. Dak.	A	Pr	Py										U.S.G.S. Bull. 765
Horne Mine, Quebec	Py	M	Pr	S	Cp	G	Au	Te					Can. Min. Jour. 53, 148-54
Horne Mine, Quebec	Py	Pr	M	Cp	Au	Te							Can. M. & M. Bull. 26, 108-40
Hyder, Alaska	Sc	Py	A	Pr	S	Cu	Cp	G	T	Cv			Ec. Geol. 22, 494-517
Insizwa, South Africa	Cp	Pe	Pr										Ec. Geol. 11, 397-402
Julian Dist., California	Py	Pr	A	Au	Te								Calif. Jour. Min. & Geol 30, 331-370
Kavelforp, Sweden	Mo	Py	A	S	Pr	Cp	G	Bi					Geol. Foren. 35, 563
Kokomo, Colorado	Py	Pr	S	Mr									Ec. Geol. 20, 54-66
Kowkash Area, Ontario	Py	Pr	Cp	S	G	Ag							Ont. Dept. Mines 40th A.R. 55-104
Litchfield, Connecticut	M	Pr	Pe	Cp									Ec. Geol. 10, 330-347
Magmatic Ore Minerals	M	H	Pr	Pe	Cp	B							Stanford Univ. Ser. 1916
Michipicoten, Ontario	Py	Pr	Cp	M									Miner. u. Petrog. 44, 349-410
Mt Bischoff, Tasmania	Ca	Pr	A	Mr	Py	Cp	G	S					Ec. Geol. 17, 153-193
Oiseau River, Manitoba	M	Py	S	Pe	Cp	Cu	M						G.M. Schwartz, Unpublished
Orange Co., Vermont	Pr	Cp	Cu										Ec. Geol. 30, 434-83
Ore Knob, North Carolina	M	Py	Pr	Cp	Cu	A	S	G					U.S.G.S. Prof. Paper 179
Panamint Dist., California	Py	Pr	Cp	M									Ec. Geol. 25, 192-200
Parry Sound, Ontario	M	Py	Pr	Cp	Cu	S							Ec. Geol. 19, 209-213
Pecos, New Mexico	Py	S	Pr	Cp									Ec. Geol. 27, 344-420
Quebec Tellurides	Py	Cp	Pr	S	Te	Au							Cont. Can. Min. 1928, 27
Robb-Montbray, Quebec	Py	Cp	Pr	S	Te	Au	Cc						Cont. Can. Min. 1928, 13
Rorgs, Norway	Py	Cp	Pr	S	M	B	Cc	G					Trans. A.I.M.E. 58, 240-64
Santa Eulalia, Mexico	M	Py	A	Pr	S	G	Py						G.M. Schwartz, Unpublished
Shakan, Alaska	Py	S	Pr	Cp	Mo								Ec. Geol. 25, 192-200
Sherritt-Gordon M, Manitoba	Pr	Cp	S	M									Ec. Geol. 24, 457-69
Singhbhum, India	M	Py	Pr	Pe	Mi	Cp							Geol. Inst. India 29, 163-172
Spring Hill, Montana	A	Pr	Py										Ec. Geol. 29, 544-59
Sudbury, Ontario	Pr	Pe	Cp										Ec. Geol. 12, 350-66
Sullivan Mine, British Col.	Pr	S	G										Eng. & Min. Jour. 122, 375-77
Torrington, Connecticut	Pr	Cp	Pe										A. J. S. (5th) 19, 185-194
Vancouver Is. Canada	M	Pr	Py	B	Cp	Cc	Cu						Ec. Geol. 22, 99-101
Wayhutta Vein, N. Carolina	Py	Pr	S	Cp	G								U.S.G.S. Prof. Paper, 179
Zimapan, Mexico	A	Pr	S	J									Ec. Geol. 9, 435-62

A - Arsenopyrite
Au - Gold
B - Bornite
Bi - Bismuthinite
Cc - Chalcocite
Co - Cobaltite
Cp - Chalcopyrite
Cu - Cubanite
Cv - Covellite
G - Galena
H - Hematite
J - Jamesonite
M - Magnetite
Mi - Millerite
Mo - Molybdenite
Mr - Marcasite
Pe - Pentlandite
Pr - Pyrrhotite
Py - Pyrite
S - Sphalerite
Sc - Scheelite
T - Tetrahedrite
Te - Tellurides

Figure 2.— Tabulation of order of formation of minerals associated with pyrrhotite.


3
Pr
P
5
P
7
M
Pr
Pr
M
Pr

pyrite as phenocrysts in pyrrhotite, some of the pyrite crystals showing corrosion. At Hitachi,[7] Japan, pyrite is partly replaced at the margins by pyrrhotite. In the Michipicoten district, Frohberg [8] noted pyrite replaced by pyrrhotite. At the Flin Flon mine [9] pyrite is described as easily replaced by pyrrhotite, and at the Horne Mine, Quebec, pyrrhotite cuts pyrite.[10]

At Lead, South Dakota, in the Homestake mine [11] pyrite is found cutting pyrrhotite. At Ducktown [12] supergene pyrite replaces pyrrhotite. At Llallagua,[13] Bolivia, pyrrhotite alters to pyrite and marcasite. Doelter [14] lists pseudomorphs of pyrite after pyrrhotite from Freiberg, but also lists pseudomorphs of pyrrhotite after pyrite from Kassel.

[7] Watanabe, M., and Landwehr, W. R.: Cupiferous pyritic deposits, Hitachi, Japan. Econ. Geol., vol. 19, pp. 434–454, 1924.

[8] Frohberg, H.: Beiträge zur Kenntnis der türmalenführenden Goldquartzgänge des Michipicotem Distriktes, Ontario. Miner. u. Petrog. Mitt., vol. 44, pp. 349–409.

[9] Brownell, G. M., and Kinkel, A. R.: Geology of the Flin Flon mine. Can. Min. Met. Bull., vol. 38, pp. 261–286, 1935.

[10] Price, Peter: The geology and ore deposits of the Home mine, Noranda, Quebec. Can. Min. Met. Bull., vol. 37, pp. 108–140, 1934.

[11] Paige, Sidney: Geology of the region around Lead, South Dakota. U. S. Geol. Surv. Bull. 765, p. 13, 1924.

[12] Ross, C. S.: Origin of the copper deposits of the Ducktown type in the Southern Appalachian region. U. S. Geol. Surv. Prof. Paper 179, 1935.

[13] Ahlfeld, F.: Die Zinnerzgrube Nucia-Llallagua (Bolivia). Metall. u. Erz, vol. 26, pp. 349–354, 1929.

[14] *Op. cit.*

Fig. 3. Euhedral pyrite crystals in pyrrhotite. Ducktown, Tenn. × 100.

Fig. 4. Pyrite (P) fragments embedded in and cut by veinlets of pyrrhotite (Pr) Ducktown, Tenn. × 125.

Fig. 5. Pyrrhotite (P) partly replaced by pyrite (light) along cleavage and carbonate (black) contacts. Posoti Claim, Santa Eulalia, Mexico. × 150.

Fig. 6. Pyrite crystal originally surrounded by pyrrhotite, which has been replaced by a second generation of pyrite and carbonate (black) Potosi Claim, Santa Eulalia, Mexico. × 150.

Fig. 7. Pyrrhotite (Pr) replaced by concentric mass of marcasite (M) along small gangue veinlet. Cuyuna Range, Minn. × 60.

Fig. 8. Pyrrhotite (Pr) replaced along a fracture by marcasite (M) Oiseau (Bird) River, Manitoba. × 200.

In several of the suites examined by the writer pyrite occurs as euhedral crystals in pyrrhotite (Fig. 3), some crystals remain apparently unaffected, others are broken and cemented without conspicuous replacement (Fig. 4), whereas still others show considerable corrosion resulting in rounded relics of pyrite.

A specimen from Ducktown, Tennessee, shows pyrite crystals apparently lining a vug but with veinlets of pyrite extending through the adjacent pyrrhotite. In pyrrohite ores from Fierro, New Mexico, most of the pyrite occurs as subhedral crystals in chalcopyrite and cubanite, but partly replaced fragments remain in pyrrhotite at places. Less common are veinlets of pyrite that cut all other minerals, suggesting two generations of pyrite, one earlier and one later than pyrrhotite. A similar relation seems to prevail in some of the specimens from pyrrhotite veins in the Homestake mine. Ore from the Sherritt-Gordon mine shows especially large crystals (up to one-half inch across) of pyrite embedded in a matrix of pyrrhotite, sphalerite and chalcopyrite. In ores from the Noranda mine pyrite is broken, corroded and surrounded by pyrrhotite; pyrrhotite areas in chalcopyrite seem to have developed around or near pyrite areas. Ore from the Makamik area in Quebec shows veinlets of pyrrhotite cutting nearly massive pyrite, the larger pyrrhotite areas commonly containing numerous pyrite fragments. Pyrite crystals also occur embedded in pyrrhotite at Sudbury.

An interesting series of specimens from the Potosi claim Santa Eulalia, Mexico, containing striking relations of pyrite and pyrrhotite were furnished the writer by Mr. W. H. Triplett. The earliest sulphide is pyrite occurring as euhedral crystals (Fig. 6), surrounded by pyrrhotite. Arsenopyrite occurs abundantly, probably closely associated in origin with pyrrhotite. Several specimens show various stages of alteration of pyrrhotite to a later generation of pyrite associated with carbonate. This alteration characteristically takes place along the cleavage of the pyrrhotite (Fig. 5) and when complete leaves a very different textural variety of pyrite (Fig. 6). The ore minerals were formed nearly at the same time, but the general sequence seems to be magnetite,

pyrite, arsenopyrite, pyrrhotite and sphalerite, galena, second generation of pyrite. The gangue is unusual, being mainly ilvaite, with some quartz, carbonate and fluorite.

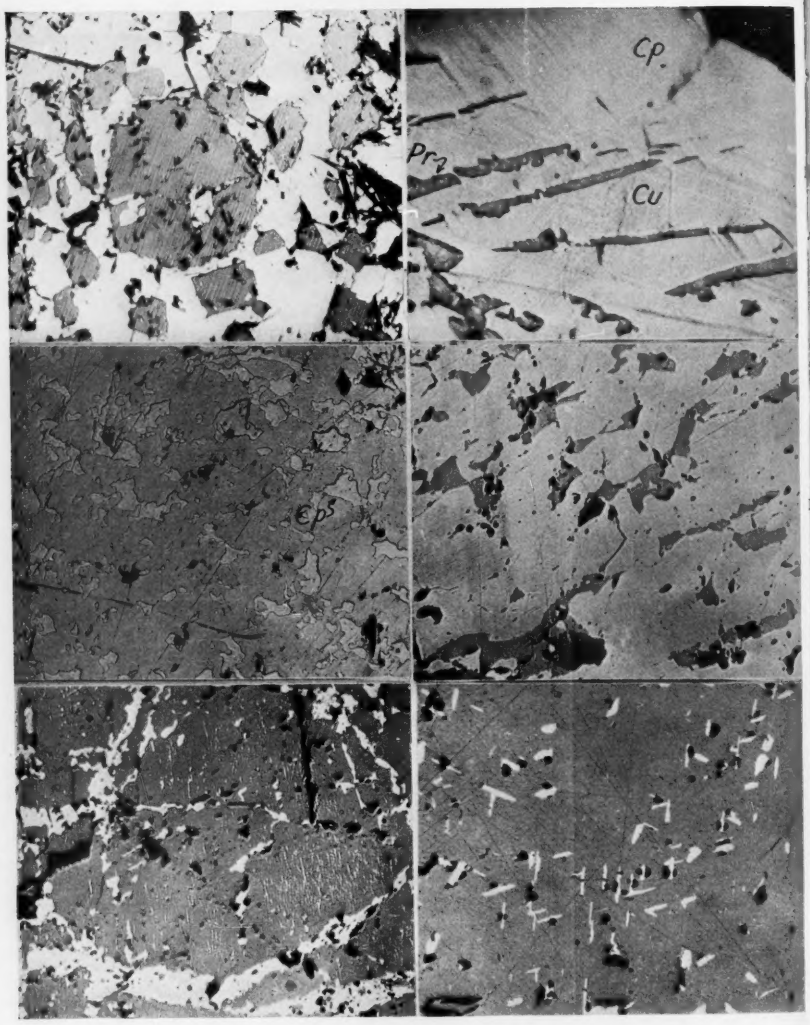
Bürg [15] in a recent paper states that the change of pyrite to pyrrhotite is commonly shown and that idiomorphic pyrite crystals develop from pyrrhotite. The writer is unable to agree with these statements on the basis of the evidence cited above. Although the minerals commonly follow each other in formation, there is only minor evidence of actual alteration of one to the other. Bürg, however, shows that it is possible to develop pseudomorphs of pyrrhotite after pyrite by heating in evacuated tubes and his sketches show several stages of alteration of a pyrite crystal. The temperature used was 600° C. and the time varied from five to fifty hours.

Marcasite.—Pyrrhotite commonly alters to marcasite or, as often stated, is replaced by marcasite (Figs. 7, 8). The most common form assumed by marcasite is as concentric shells and globular masses. Several examples are described by Newhouse [16] in his discussion of marcasite. He believes it develops in pyrrhotite ores both by hypogene and supergene action; for example, an association with carbonate, quartz and pyrite suggests hypogene marcasite. The supergene type is characterized by well developed veinlets that cut pyrrhotite and other sulphides.

A review of the literature shows that marcasite was listed in 18 of 86 pyrrhotite occurrences (Fig. 1). In papers cited elsewhere it has been described as definitely replacing pyrrhotite at the Aldermac mine, Quebec; Atlin, B. C.; Angangueo, Mexico; Cuyuna district, Minnesota; Ducktown, Tennessee; Kokomo, Colorado; Kaveltorp, Sweden; Llallagua, Bolivia; Mt. Bischoff, Tasmania; Michipicoten, Ontario; Panamint district, California; and the Snipe Bay and Tasmania claims, Alaska. Doelter notes that pseudomorphs of marcasite after pyrrhotite have been described from Freiberg.

[15] Bürg, G.: Eine mikroskopische Studie der Dissoziation des Pyrits zu Magnetkies. Z. prakt. Geol., vol. 42, pp. 177–184, 1934.

[16] Newhouse, W. H.: Paragenesis of marcasite. ECON. GEOL., vol. 20, pp. 54–66, 1925.



9

11

13

In the Panamint [17] district, siderite and marcasite replace massive pyrrhotite and marcasite is considered hypogene because quartz is later. Schneiderhöhn [18] has described the alteration of siderite to pyrrhotite, followed by pyrite, then pyrite and marcasite mixed and finally marcasite alone. Such an example leaves no doubt that marcasite may be of late hypogene as well as the more common supergene origin. From this occurrence Schneiderhöhn deduced the following range of stability

Pyrrhotite above 565° C.
Pyrrhotite + pyrite around 565° C.
Pyrite between 565° C. and about 400° C.
Pyrite + marcasite between 400° C. and 300° C.
Marcasite below 300° C.

Gilbert [19] has emphasized the formation of grating structure by alteration of pyrrhotite to marcasite at Ducktown.

Magnetite.—Since magnetite also is a characteristic mineral of the high temperature deposits it is a common associate of pyrrhotite. Of the 86 districts tabulated, 38 show associated magnetite. Wherever found directly associated so that the relations may be observed microscopically, magnetite normally occurs as

[17] MacMurphy, F.: Geology of the Panamint silver district, California. Econ. Geol., vol. 25, pp. 305–325, 1930.

[18] Schneiderhöhn, H.: Verläufige Mitteilung über pyrometamorphe Paragenesen in den Siegerländer Spateisensteingängen: Z. Krist., vol. 58, pp. 309–329, 1923.

[19] *Op. cit.*

Fig. 9. Magnetite grains and crystals in a matrix of pyrrhotite. Atikokan district, Ont. × 100.

Fig. 10. Blades of pyrrhotite (Pr) in an intergrowth of chalcopyrite (Cp) and cubanite (Cu). Parry Sound, Ont. × 200.

Fig. 11. Angular, evidently unreplaced inclusions of chalcopyrite (Cp) in pyrrhotite. Ducktown, Tenn. × 125.

Fig. 12. Sphalerite (gray) inclusions in pyrrhotite, a mutual relation. Sullivan Mine, Kimberley, B. C. × 50.

Fig. 13. Pyrrhotite included in sphalerite and occurring along grain boundaries. Pyrrhotite a replacement of sphalerite, according to Shenon. Cowboy Mine, Oregon. × 100.

Fig. 14. Pyrrhotite as lath-like inclusions along the crystallographic planes of sphalerite. Potosi Claim, Santa Eulalia, Mexico. × 225.

anhedral to euhedral grains surrounded by pyrrhotite, or lying in a matrix of pyrrhotite (Fig. 9). Replacement of the magnetite is not common, but the distinctly rounded nature of some isolated magnetite grains suggests corrosion during the deposition of the pyrrhotite. Commonly in high temperature deposits, the oxides precede the deposition of the sulphides. The relations of magnetite and pyrrhotite seem to bear out this generalization. For example, Tolman and Rogers [20] give a definite order of formation in the magmatic ores and list magnetite first, followed by hematite, then pyrrhotite and state that there is definite replacement of one magmatic mineral by another. Howe [21] described magnetite replaced by pyrrhotite at Litchfield, Connecticut. At Copper Cliff mine [22] rounded grains of magnetite in pyrrhotite have been noted.

Wernicke [23] on the other hand found magnetite and pyrrhotite intergrown with mutual boundaries, and Ross [24] has described magnetite cutting across a crystal of pyrrhotite from Fontana, North Carolina.

The writer has observed magnetite, evidently earlier than pyrrhotite, in ores from Fierro, New Mexico; Bird River, Manitoba; Atikokan and Parry Sound, Ontario. The relatively strong crystallizing power of magnetite [25] suggests caution in determining age relations simply on the basis of embedded grains or crystals of magnetite in pyrrhotite.

Frebold [26] shows examples of the alteration (umwandlung) of pyrrhotite to magnetite and of magnetite to pyrrhotite.

[20] Tolman, C. F., and Rogers, A. F.: A study of magmatic sulphide ores. Leland Stanford Univ. Pub., 1916.

[21] Howe, E.: Sulphide bearing rocks from Litchfield, Connecticut. Econ. Geol., vol. 10, pp. 330–347, 1915.

[22] Campbell, Wm., and Knight, C. W.: On the microstructure of nickeliferous pyrrhotite. Econ. Geol., vol. 2, pp. 350–366, 1907.

[23] Wernicke, F.: Magnetkiesparagenesen von Sachsichen Lagerstätten. Min. pet. Mitt., vol. 44, pp. 403–469.

[24] Ross, C. S.: Origin of copper deposits of the Ducktown type in the Southern Appalachian region. U. S. Geol. Surv. Prof. Paper 179, pl. 38, 1935.

[25] Schwartz, G. M.: Magnetite metacrysts. Am. Min., vol. 21, pp. 635–641, 1936.

[26] Frebold, G.: Beiträge zur Kenntnis der Erzlagerstätten des Harzes. Centralb. f. Min., 1926, pp. 323–332.

In summary it may be said that magnetite is normally earlier than pyrrhotite, but that in rare cases magnetite probably follows pyrrhotite in formation.

Schneiderhöhn and Ramdohr [27] illustrate an excellent example of an eutectic texture between pyrrhotite and magnetite with the former in excess.

Hematite.—Pyrrhotite is rarely found with hematite; in fact Gilbert [28] has inferred an antipathy between hematite and pyrrhotite and noted in the suites he examined from Sudbury, Rossland, Sullivan mine, Coeur d'Alene and Gossan Lead, that although magnetite is present, hematite was not observed. A review of the literature by Gilbert supported the generalization and he suggested that hematite and pyrrhotite represent the extremes of oxidizing and reducing conditions.

In the present investigation the writer found Gilbert's generalization to hold true with possibly rare exceptions. Tolman and Rogers [29] list hematite between magnetite-ilmenite and pyrrhotite in the order of formation of magmatic minerals, but since this is a generalization it does not mean that pyrrhotite occurs directly with hematite although it would be inferred that it does. Butterfield [30] lists specularite in quartz veinlets that cut sulphides in the Horne mine, and pyrrhotite occurs in the sulphides. This also does not necessarily imply a direct association. Hematite is found with magnetite in the Parry Sound ores but careful search by the writer has failed to reveal it in the same polished specimen with pyrrhotite.

Chalcopyrite.—Chalcopyrite is an almost universal associate of pyrrhotite, as is shown by the fact that it was reported in all but seven of the eighty-six deposits tabulated, and it is possible that detailed microscopic study of polished surfaces would reveal chalcopyrite where it has not been recorded. This association emphasizes the fact that chalcopyrite is the principal copper min-

[27] *Op cit.*, Fig. 59.

[28] Gilbert, G.: Significance of hematite in certain ore deposits. ECON. GEOL., vol. 21, pp. 360–377, 1926.

[29] *Op. cit.*

[30] Butterfield, H. M.: Geology of the Horne mine. Can. Min. Jour., vol. 55, pp. 148–154, 1934.

eral in all of the higher temperature copper deposits. Chalcopyrite is in places contemporaneous with pyrrhotite, especially in the truly magmatic occurrences, but it is much more common to find it later; thus of 56 districts for which the order of minerals was tabulated, 43 showed chalcopyrite later than pyrrhotite. In three occurrences chalcopyrite and pyrrhotite were listed as contemporaneous and in three chalcopyrite was listed as earlier. Graton and Murdoch [31] concluded as a result of their studies in 1913 that chalcopyrite is in the main later than pyrrhotite. Some of the evidence for this sequence may be briefly reviewed.

Chalcopyrite occurs as veinlets in pyrrhotite at Rossland, British Columbia; [32] Amulet Mine, Quebec; [33] Mount Nickel [34] and Ducktown.[35] It is recorded that pyrrhotite is replaced by chalcopyrite at Flin Flon, Manitoba;[36] Pecos, New Mexico;[37] Hodges, Connecticut; [38] Michipicoten [39] and Atikokan, Ontario.[40] In Orange County, Vermont,[41] alternating bands of chalcopyrite and pyrite suggest a contemporaneous relation. At the Waite-Ackerman mine, Quebec,[42] pyrrhotite occurs between crystals of chalcopyrite, as curving wisps each being a single crystal.

[31] Graton, L. C., and Murdoch, J.: The sulphide ores of copper. Am. Inst. Min. Eng. Trans., vol. 45, pp. 26–81, 1913.

[32] Drysdale: Geology and ore deposits of Rossland, B. C. Memoir 77, Can. Geol. Surv., 1915.

[33] Wilson, M. E.: Amulet Mine, Noranda district, Quebec. Can. Geol. Surv. Summ. Rept. 1933 D, p. 83.

[34] Campbell, Wm., and Knight, C. W.: On the microstructure of nickeliferous pyrrhotite. Econ. Geol., vol. 2, pp. 350–366, 1907.

[35] Ross, C. S.: *Op cit.*

[36] Brownell, G. M., and Hinkel, A. R.: *Op. cit.*

[37] Krieger, P.: Geology of the zinc-lead deposit at Pecos, New Mexico. Econ. Geol., vol. 27, pp. 344–364; 450–470, 1932.

[38] Ager, W. M.: The Hodges Nickel Prospect, Torrington, Connecticut. Am. Jour. Sci., 5th ser., vol. 19, pp. 185–194, 1930.

[39] Frohberg, H.: *Op. cit.*

[40] Hawley, J. E.: Geology of the Sapawe Lake area. Ont. Dept. Mines, 38th Ann. Rept. (6), pp. 1–58, 1930.

[41] Buerger, N. W.: The copper ores of Orange County, Vermont. Econ Geol., vol. 30, pp. 434–443, 1935.

[42] Stevenson, J. S.: Vein-like masses of pyrrhotite in chalcopyrite from Waite-Ackerman-Montgomery mine. Am. Min., vol. 18, pp. 444–449, 1930.

In the Flaad Mine,[43] Norway, oriented pentlandite and chalcopyrite in strained pyrrhotite suggest a contemporaneous relation as do intergrowths described by Goodchild from Insizwa and also those noted by Schwartz [44] from Cook County, Minnesota.

In specimens from Ducktown the writer observed chalcopyrite included in pyrrhotite without evidence of replacement (Fig. 11); also chalcopyrite and pyrrhotite in the same veinlet. Chalcopyrite also was noted along the boundaries of sphalerite and pyrrhotite, suggesting that part of the chalcopyrite was later in origin. Ore from the Noranda mine shows somewhat corroded areas of pyrrhotite in chalcopyrite. All of the available evidence indicates a close relationship between pyrrhotite and chalcopyrite, with the minerals forming contemporaneously in part, but with the bulk of the chalcopyrite somewhat later than pyrrhotite.

Sphalerite.—Sphalerite is a common associate of pyrrhotite, occurring in 53 out of 86 deposits tabulated. It normally forms with or later than pyrrhotite as shown by Fig. 2. At the Sullivan Mine, Kimberly, B. C.,[45] for example, the relations suggest that sphalerite and pyrrhotite formed at the same time (Fig. 12). A similar condition was noted by Emmons and Laney [46] at Ducktown. They state "By far the greater part of the sphalerite appears to have been deposited contemporaneously with pyrrhotite, chalcopyrite and galena." Ross [47] believed pyrrhotite and sphalerite to be partly contemporaneous, but that most of the sphalerite followed pyrrhotite in the Ducktown deposits.

Shenon [48] has recently shown that pyrrhotite replaces sphalerite

[43] Goodchild, W. H.: The origin and occurrence of crystallographic intergrowths. Econ. Geol., vol. 11, pp. 397–402, 1916.

[44] Schwartz, G. M.: A sulphide diabase from Cook County, Minnesota. Econ. Geol., vol. 20, pp. 201–205, 1925.

[45] Schwartz, G. M.: Microscopic character of the Sullivan ores. Eng. Min. Jour., vol. 123, pp. 275–277, 1926.

[46] Emmons, W. H., and Laney, F. B.: Geology and ore deposits of the Ducktown mining district, Tennessee. U. S. Geol. Surv. Prof. Paper 139, p. 47, 1926.

[47] Ross, C. S.: *Op. cit.*

[48] Shenon, P. J.: A massive sulphide deposit of hydrothermal origin in serpentine. Econ. Geol., vol. 27, pp. 597–613, 1932.

at the Cowboy mine in Oregon (Fig. 13). Gärtner [49] shows blades of pyrrhotite in sphalerite.

Eitel [50] suggests that pyrrhotite and sphalerite form an isomorphous mixture at high temperature, and Schneiderhöhn and Ramdohr [51] show pyrrhotite as an unmixing product in sphalerite.

Thompson [52] described cracks in sphalerite filled with pyrrhotite in ores from Latouche Island, Alaska, and a similar relation has been described for the Hitachi mines of Japan.[53]

In the majority of the specimens studied that contain both sphalerite and pyrrhotite, the minerals seem to have a more completely mutual relation than any other combination with pyrrhotite, except possibly pentlandite. It seems possible for them to precipitate at the same time with either one in excess. The so-called emulsion structure with minute rounded inclusions of pyrrhotite in sphalerite was observed notably in ores from the Potosi Claim, Chihuahua, Mexico. Good oriented inclusions of pyrrhotite were also observed in those same ores (Fig. 14).

Pentlandite.—Pyrrhotite commonly occurs without visible pentlandite, but pentlandite is rarely if ever found without pyrrhotite. Only 16 of the 86 occurrences of pyrrhotite tabulated were found to have pentlandite associated. The relation between the two minerals has been carefully and completely described as found in the nickel ores of Sudbury, and to a less extent elsewhere. The two minerals are so closely related that they must have formed contemporaneously or very nearly so. Van der Veen [54] has suggested that pentlandite occurred in solid solution in pyrrhotite at Sudbury, but rather completely segregated during slow cooling. Newhouse has shown that nickel will dissolve in pyrrhotite up to

[49] Gärtner, Karl: Erzmikroskopische und gefügeanalytische Untersuchung im Bereiche der westlichen Haupstörung des Rammelsbergs. Chemie der Erde, vol. 9, pp. 22–49, 1934.

[50] Eitel, W.: Über das Vorkommen des Zinkblend im Basalt des Buhls bei Kassel. Centralb. f. Min., pp. 273–285, 1920.

[51] *Op cit.*, p. 136.

[52] Thompson, A. P.: The relations of pyrrhotite to chalcopyrite and other sulphides. School of Mines Quart., vol. 34, no. 4, 1913.

[53] Watanabe, M., and Landwehr, W. R.: Cupiferous pyritic deposits, Hitachi Mines, Japan. Econ. Geol., vol. 19, pp. 434–454, 1924.

[54] Van der Veen, R. W.: Mineragraphy and ore deposition. 1925.

13 per cent. at high temperatures, but breaks down below about 600° C. to leave pyrrhotite and pentlandite. Ehrenberg[55] has described oriented intergrowths of pentlandite in three directions in pyrrhotite from Miggiandone and skeleton crystals of pentlandite with rays in six directions from Sudbury.

The normal occurrence of pentlandite is as grains equigranular with pyrrhotite and as smaller grains and stringer-like masses along the borders of pyrrhotite grains.

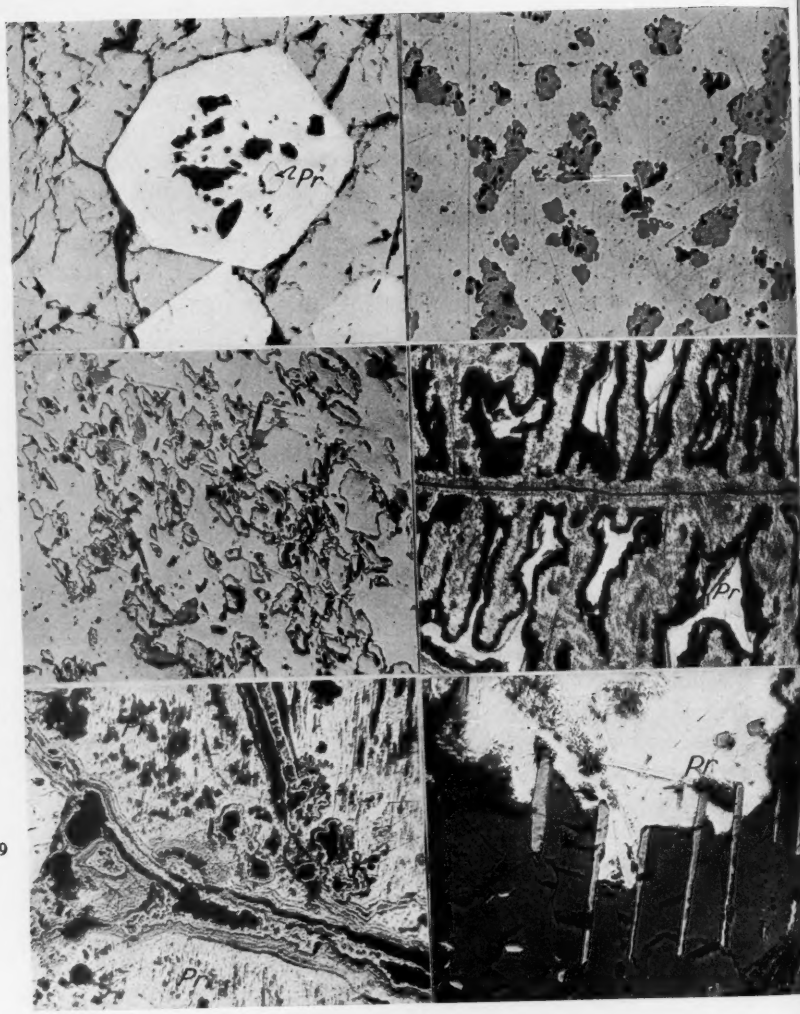
Cubanite (*chalmersite*).—One of the most interesting minerals closely associated with pyrrhotite is cubanite, also known as chalmersite (Fig. 10). Although pyrrhotite occurs abundantly with chalcopyrite without cubanite, the latter mineral is not known to occur except with these two minerals. The normal occurrence is as a bladed crystallographic intergrowth of cubanite in chalcopyrite with the cubanite blades ending abruptly against areas of pyrrhotite. In some specimens areas of cubanite seem to have developed in the chalcopyrite around areas of pyrrhotite but without forming crystallographic intergrowths. This relation suggests that the cubanite developed by reaction perhaps during deposition between the crystallizing chalcopyrite and pyrrhotite. Chemically, cubanite occupies a position intermediate between chalcopyrite and pyrrhotite, a further indication of the above assumption. That the relations between chalcopyrite, pyrrhotite, cubanite and closely related minerals are complex is brought out in detail in a recent paper by Borchert.[56]

Borchert believes that chalcopyrrhotite decomposes into chalcopyrite and pyrrhotite by very slow cooling between 255° and 235° and by very slow cooling below 235° separates into cubanite and pyrrhotite or into chalcopyrite, cubanite and pyrrhotite.

Arsenopyrite.—Arsenopyrite is a common associate of pyrrhotite since it also occurs most abundantly in the higher temperature deposits. In the tabulated associations arsenopyrite was noted in 31 of 86 districts. Arsenopyrite has a fairly strong crystallizing

[55] Ehrenberg H.: Oierntierte Verwachsungen von Magnetkies und Pentlandit. Z. Krist., vol. 82, pp. 309–315, 1922.

[56] Borchert, H.: Über Entmischungen im System Cu-Fe-S und ihre Bedeutung als "Geologische Thermometer," Chemie der Erde, vol. 9, pp. 145–172, 1934.


15
Pr
17
Pr
19
Pr
Pr

power and therefore occurs as subhedral to euhedral crystals. This is in contrast to pyrrhotite, which rarely shows any external crystal form. It is common, therefore, to find grains and crystals of arsenopyrite embedded in a matrix of pyrrhotite (Fig. 15). This occurrence generally leads to the suggestion that arsenopyrite is older, but other criteria should be applied before drawing a conclusion. As a matter of fact arsenopyrite commonly seems to be older and fragments are cemented or replaced by pyrrhotite. Thus at Hyder, Alaska,[57] arsenopyrite is cut by pyrrhotite veins and at Banksfield,[58] Canada, pyrrhotite occurs as short veins and blebs in arsenopyrite. In the Homestake mine arsenopyrite characteristically occurs as euhedral crystals in schist with pyrrhotite strung out parallel to the schistosity, but pyrrhotite also cuts arsenopyrite as veinlets and pyrrhotite has been placed later in origin by several investigators. Arsenopyrite in some specimens is shattered and replaced by pyrrhotite, but arsenopyrite crystals with abundant inclusions of pyrrhotite (Fig. 16) suggest some pyrrhotite was forming at the time arsenopyrite crystallized, but the bulk of the pyrrhotite was somewhat later. Cross veins of massive pyrrhotite are probably still later.

Frohberg[59] shows an excellent photograph of an arsenopyrite

[57] Jewell, W. B.: Mineral deposits of the Hyder district, southeastern Alaska. Econ. Geol., vol. 22, pp. 494–517, 1927.

[58] Thomson, E.: Mineralization in the Little Long Lac and Sturgis River areas: Univ. Tor. Studies, vol. 38, pp. 37–45, 1935.

[59] *Op. cit.*, table 10, figure 10.

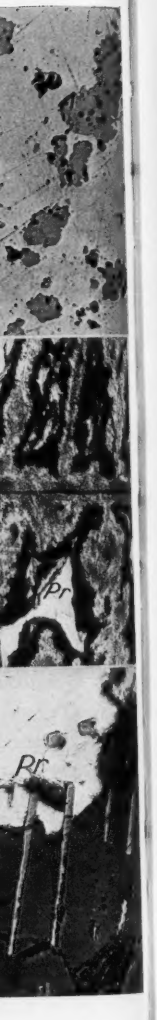


Fig. 15. Arsenopyrite crystal in pyrrhotite. Gangue (dark) and pyrrhotite (Pr) inclusions occur in arsenopyrite. Homestead Mine, Lead, S. D. × 50.

Fig. 16. Pyrrhotite inclusions in arsenopyrite. Homestake Mine, Lead, S. D. × 80.

Fig. 17. Rounded inclusions of pyrrhotite in galena. Sullivan Mine, Kimberley, B. C. ×50.

Fig. 18. Violarite with remnants of pyrrhotite (Pr). Oiseau (Bird) River, Manitoba. × 100.

Fig. 19. "Limonite" which has replaced pyrrhotite (Pr) along veinlets. Cook County, Minn. × 60.

Fig. 20. Ilmenite blades along the cleavage of silicate (dark) that has been partly replaced by pyrrhotite (Pr). Sudbury, Ont. × 100.

crystal from the Michipicoten district with the inner part replaced by pyrrhotite.

At the Flin Flon mine [60] arsenopyrite has been described as contemporaneous with or earlier than pyrrhotite. Newhouse [61] found pyrrhotite embaying arsenopyrite from Angangue, Mexico. Donnelly [62] however, found arsenopyrite later than pyrrhotite in the Julian district, California.

Galena.—Although galena is not a characteristic high temperature mineral, it is common (38 out of 86 districts tabulated) in small amounts associated with pyrrhotite, and in the Sullivan mine, Kimberly, B. C., occurs in large amounts with sphalerite and pyrrhotite.[63] The evidence in the Sullivan ores strongly suggests that the galena crystallized later than the pyrrhotite (Fig. 17) and sphalerite, and this seems to be the normal relationship, as much the same evidence is found at Ducktown, Tennessee.

At Mount Nickel [64] galena occurs in veins with sphalerite, chalcopyrite, and quartz cutting pyrrhotite. At the East Hecla Mine [65] pyrrhotite is strung out in galena flowage ores and broken pyrrhotite is cemented by galena.

Galena is probably always of later origin than pyrrhotite; at least no exceptions were found by the writer.

Bornite.—As pointed out by Gilbert [66] there appears to be an antipathy between bornite and pyrrhotite in contrast to almost constant association of chalcopyrite and pyrrhotite. Gilbert suggested that bornite occurs in high temperature deposits only where iron is not abundant. This does not seem to be true in copper ores from Engels, California, or Parry Sound, Ontario, where

[60] Brownell, G. M., and Hinkel, A. R.: *Op. cit.*

[61] Newhouse, W. H.: Paragenesis of marcasite. ECON. GEOL., vol. 20, pp. 54–66, 1925.

[62] Donnelly, M.: Geology and mineral deposits of the Julian district, San Diego County, California. Cal. Jour. Mines and Geol., vol. 30, pp. 331–370, 1935.

[63] Schwartz, G. M.: Microscopic character of the Sullivan ores. Eng. and Min. Jour., vol. 122, pp. 375–377, 1926.

[64] Campbell, Wm., and Knight, C. W.: *Op. cit.*

[65] Waldschmidt, W. A.: Deformation of ores Coeur d'Alene district, Idaho. ECON. GEOL., vol. 20, pp. 573–586, 1925.

[66] Gilbert, G.: Antipathy of bornite and pyrrhotite. ECON. GEOL., vol. 20, pp. 647–670, 1925.

magnetite and bornite are intimately and abundantly associated. Osborne [67] has pointed out an exception to Gilbert's generalization at the Jeune group on Vancouver Island, where bornite in veinlets cuts magnetite, pyrrhotite, and pyrite with bornite in direct contact with pyrrhotite. Nevertheless Gilbert's generalization is a good one because no other direct association of the two minerals was noted either in the literature or in the specimens studied in the laboratory. The reason for the antipathy, however, is not evident.

Gold.—There is abundant evidence presented in the literature that gold is commonly associated with pyrrhotite. In some districts there is definite evidence of a direct association of native gold and gold tellurides such as the occurrence of the latter in veinlets in the pyrrhotite. In other districts, although pyrrhotite may be present, the gold does not seem to be intimately connected with it. Thus, studies of ores from the Homestake mine show gold with arsenopyrite, chlorite, quartz and less commonly with other minerals, but the abundant pyrrhotite seems to carry relatively slight values.

The question of the association of gold with various minerals is being studied under the writer's direction and it is hoped to present detailed evidence in a later paper.

Other Minerals.—There are many other ore minerals that are occasionally associated with pyrrhotite, but few if any of them are significant enough to require detailed description. Among these are chalcocite, covellite, " limonite," tetrahedrite, jamesonite, scheelite, titanite, cobaltite, millerite, ilmenite, violarite, cassiterite, bismuthinite, molybdenite, wolframite and stannite. Chalcocite and covellite are characteristically precipitated by pyrrhotite during secondary enrichment of copper-bearing pyrrhotite deposits such as those of Ducktown. As discussed in some detail by Emmons,[68] pyrrhotite is readily attacked by acid solutions and in turn pyrrhotite readily precipitates copper sulphide so that the zone of enrichment is thinner and richer than in deposits lacking pyrrhotite.

[67] Osborne, F. F.: Discussion. ECON. GEOL., vol. 22, pp. 99–101, 1927.

[68] Emmons, W. H.: Enrichment of ore deposits. U. S. Geol. Surv. Bull. 625, 1917.

In the enriched zone at Ducktown chalcocite and covellite coat pyrrhotite.

In nickel deposits pyrrhotite may be replaced by violarite (Fig. 18), which commonly occurs as a supergene replacement of pentlandite associated with the pyrrhotite. On being attacked by ordinary weathering pyrrhotite readily alters to "limonite" (Fig. 19).

Dunn [69] has described pyrrhotite replaced by millerite at Singhbhum, India.

Gangue and Rock Minerals.—Pyrrhotite in common with other abundant sulphides seems to replace almost any gangue or rock mineral. Quartz and carbonates are probably most frequently noted in the literature but amphiboles, pyroxenes, feldspars, olivine are also commonly replaced and many others are noted in individual districts.

Basic igneous rocks are likely to contain at least small amounts of pyrrhotite, but large amounts, in connection with ores, replace limestone, quartzite, and various igneous rocks. In many basic igneous rocks pyrrhotite may be a primary mineral occurring with igneous rock textures.

Specific replacement of siderite by pyrrhotite has been described for the Panamint district. Pyroxene is replaced by pyrrhotite at Sudbury and in many magmatic deposits (Fig. 20).

Schneiderhöhn [70] has described the paragenesis in detail of the alteration of siderite to pyrrhotite, marcasite and pyrite of the Siegerländer deposits as noted above.

Frebold [71] shows inclusions of plagioclase in pyrrhotite and Bastin found pyrrhotite allotriomorphic with olivine in Knox County, Maine.[72] Pyrrhotite replaces quartz, carbonates and amphiboles in the Cuyuna district of Minnesota.[73]

[69] Dunn, J. A.: Sulphide mineralization in Singhbhum, India. India Min. Geol. Inst. Trans., 29 (2), pp. 163–172, 1934.

[70] *Op. cit.*

[71] Frebold, G.: *op. cit.*

[72] Bastin, E. S.: A pyrrhotitic peridotite from Knox County, Maine. Jour. Geol., vol. 16, pp. 124–138, 1908.

[73] Thiel, G. A.: Iron sulphides in magnetic belts near the Cuyuna range. ECON. GEOL., vol. 19, pp. 466–472, 1924.

No attempt was made to study in detail the relations of pyrrhotite to gangue and rock minerals. The above are simply typical.

Summary of Paragenesis.

The minerals most commonly associated with pyrrhotite in order are: chalcopyrite, pyrite, sphalerite, arsenopyrite, magnetite, galena, pentlandite, cubanite and marcasite. Of these pyrite, magnetite and arsenopyrite are normally earlier than pyrrhotite, but exceptions are known, being especially important in the case of pyrite. Sphalerite and pentlandite are characteristically contemporaneous with pyrrhotite, but commonly show a continuation of deposition beyond the latter. Chalcopyrite, galena and marcasite are normally later than pyrrhotite. Chalcopyrite has formed contemporaneously and possibly earlier in rare cases, but galena and marcasite are invariably later.

The most interesting relations are shown by the three iron sulphides, pyrite, pyrrhotite and marcasite. Many districts show that pyrite characteristically forms first, commonly as euhedral crystals, followed by massive pyrrhotite which generally has not affected the pyrite but in some examples has replaced it. At a still later time pyrite may replace the pyrrhotite. In other examples marcasite rather than pyrite replaces the pyrrhotite as a late hypogene stage, or more commonly as a result of supergene action.

DISCUSSION.

It is of interest to consider the relations of the iron sulphides in the light of known data on the formation of the various sulphides.

It has been shown that pyrrhotite may be synthesized from pyrite by heating in H_2S above 575° C.[74] There is no reason to doubt that this origin accounts for some pyrrhotite, but that it does not account for the bulk of known pyrrhotite is shown beyond reasonable doubt by the evidence presented above. Pyrite is a common associate of pyrrhotite and usually shows little if any replacement by the pyrrhotite as would be necessary if the

[74] Allen, E. T., Crenshaw, J. E., and Johnston, J.: The mineral sulphides of iron. Am. Jour. Sci., vol. 33, pp. 169–236, 1912.

pyrrhotite had formed by the alteration of pyrite. It was shown in the paper last cited that at 550° the reaction which results in pyrite forming pyrrhotite is readily reversible. Thus, pyrite may replace pyrrhotite, and the example described above from the Santa Eulalia district, Mexico, is believed to represent the change of pyrrhotite to pyrite, but evidently this happens only rarely as few analogous examples have been described.

The same reasoning would seem to apply to the formation of pyrrhotite by the attack of alkali sulphide solutions on pyrite, as shown by Stevens.[75] If much pyrrhotite were formed in nature by such reactions the pyrite should either have disappeared or have shown conspicuous attack; these effects are not common.

Burg [76] has shown that pyrite crystals may be altered to pyrrhotite by heating in evacuated tubes, but here too the scarcity of pseudomorphs of pyrrhotite after pyrite indicates that this is not an important process in nature.

Pyrrhotite alters readily to marcasite under attack of acid solutions at low temperature. Schneiderhöhn [77] emphasizes the formation of marcasite below 300° following pyrrhotite and pyrite in an example of hypogene mineralization.

Gilbert [78] has discussed the probable chemical origin of marcasite in connection with its formation from pyrrhotite at Ducktown and believes it is a result especially of the action of H_2S during the alteration of pyrrhotite by sulphuric acid formed by oxidation of sulphides. He represents the chemical action by the following reaction derived from the work of Allen.

$$Fe_2(SO_4)_3 + 2H_2S = 2H_2SO_4 + FeS_2 + H_2SO_4$$

Newhouse [79] has concluded that certain described occurrences of marcasite with an association of carbonate, pyrite and quartz are of hypogene origin with neutral or nearly neutral solutions.

[75] Stevens, R. E.: The alteration of pyrite to pyrrhotite by alkali sulphide solutions. ECON. GEOL., vol. 28, pp. 1–19, 1933.

[76] Burg, E.: *Op. cit.*

[77] Schneiderhöhn: *Op. cit.*

[78] Gilbert, G.: Oxidation and enrichment at Ducktown, Tennessee. Am. Inst. Min. Met. Eng. Trans., vol. 70, pp. 978–1023, 1924.

[79] *Op. cit.*

Experimental production of marcasite of this type does not seem to have been accomplished.

The simplest explanation for pyrrhotite following pyrite in most deposits is that as the amount of available sulphur decreased pyrrhotite was formed. This, however, seems inadequate when it is considered that most of the normal sulphides follow pyrrhotite in the order of paragenesis and this gives little suggestion of a deficiency of sulphur; for example $CuFeS_2$, ZnS, PbS would scarcely be said to form after sulphur had become deficient. It seems, rather, that a proper combination of sulphur concentration, pressure and temperature gives the conditions that result in the crystallization of pyrrhotite rather than pyrite and the limitation of pyrrhotite to magmatic, pyrometasomatic and hypothermal deposits indicates that high pressure and temperature are necessary, but apparently one or more of these factors favors precipitation of pyrite during the initial stages of deposition of these deposits.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
December 15, 1936.

PETROGRAPHIC STUDY OF GOLD PROSPECTS OF MINNESOTA.

FRANK F. GROUT.[1]

INTRODUCTION.

GOLD has been found in Minnesota in small amounts since 1865, and there was a small production in 1894 and 1895 from the Little American Mine at Rainy Lake on the Ontario boundary. Exploration and investment have continued and many prospects have been opened up, but no general study has been made of the character of the material since modern methods of classification of ores have been adopted. There is no *a priori* reason to believe that the region is unfavorable geologically for gold deposits, but emphasis should be put on the long record of unsuccessful exploration, and investors should be warned not to be optimistic.

In the reports of the Geological and Natural History Survey of Minnesota there are several references to gold prospects [2] and the activity at Rainy Lake was given prompt and careful study.[3] Volume V of the Final Reports has petrographic descriptions of several of the vein materials, but these are scattered among descriptions of miscellaneous rocks and can now be somewhat revised and extended to cover more recent exploration. A few other papers contain brief references to the prospects.[4]

The chance to collect and examine these materials has come to

[1] Published by permission of the Director of the Minnesota Geological Survey.

[2] Minn. Geol. and Nat. Hist. Surv. 7th Ann. Rept., pp. 23–4, 1879. 16th Ann. Rept., p. 284, 1888. 18th Ann. Rept., pp. 20–1, 1890. 23rd Ann. Rept., pp. 36–148, 1895. Final Rept., vol. 1, p. 95, 1884. Vol. 2, p. 436, 1888. Vol. 4, pp. 23, 155, 192–211, 258 and 528, 1899. Vol. 5, pp. 330, 350 to 352, 359, 361, 732, 842, 1900.

[3] *Idem*, 23rd Ann. Rept. and Final Rept., vol. 5, pp. 192–211.

[4] Kloos, J.: Geologische Notizen aus Minnesota. Zeit. deut. geol. Ges., vol. 23, pp. 417–448, 1871. Coleman, A. P.: Gold in Ontario. Ont. Bur. of Mines. 4th Ann. Rept., pp. 41–58, 1895; 5th Ann. Rept., pp. 62–3, 1896; 6th Ann. Rept., pp. 80 and 115, 1897.

the writer in the course of many years' work on the Geological Survey and grateful acknowledgment is here given the Director, W. H. Emmons, for the opportunity to visit the prospects. Thanks are due also to the Graduate School Funds for research at the University of Minnesota for assistants and for aid in the preparation of thin sections. Dr. J. W. Gruner has recently sampled many mineralized zones, and had them assayed without any encouraging results. Aside from an occasional find of "colors" in the glacial drift, the gold prospects are in the pre-Cambrian.

THE LITTLE AMERICAN MINE AT RAINY LAKE.

The Little American mine is on a small island near the south shore of Rainy Lake in the NW¼ Sec. 33, T. 71 N., R. 22 W. It produced in 1894 and 1895 several thousand dollars of gold.[5] The ore was stamp milled on the mainland near the island, yielding about $17.00 per ton. In 1895 a new shaft was sunk and a steam hoist was operating. At that time the district was not accessible by railway, and the expense of bringing in the mill and supplies was very great. There was little to encourage the large expenditures, and when the mining operations ran into difficulties the mine was abandoned. The high water caused by the power development at the outlet of Rainy Lake has since reduced the area of the island and raised the water into the open cut so that it would be more difficult now to work on the island than before, but the high price of gold has led to some renewed interest in the deposit which is now easily reached by boat from a near-by road, twelve miles from International Falls.

H. V. Winchell and U. S. Grant in 1895 wrote a report on the geology of the gold region for the Minnesota Survey.[6] This needs only a slight revision from field data of recent years. They

[5] Production reported by H. V. Winchell and U. S. Grant, Minn. Geol. and Nat. Hist. Surv., 23rd Ann. Rept., was $4,635.33 in 1894. Production of gold in Minnesota for the years following, to 1900, is recorded in Mineral Resources of the United States, but the total for all these years is less than that of three months in 1894.

[6] Winchell, H. V., and Grant, U. S.: Minn. Geol. and Nat. Hist. Surv., 23rd Ann. Rept., pp. 36–105, 1895; largely reprinted in Final Report, vol. 4, pp. 192–211, 1899.

reported no petrographic work but noted certain features of the ore.

The geology of the district has been studied by several men with considerable difference of opinion. Suffice it to say that the prominent biotite schists of the Minnesota shore were once supposed to be older than the Keewatin greenstone, but the rocks are highly recrystallized, folded and faulted, and their succession is determined only by the most detailed study of the cross bedding, gradation of grain and other structures. It has seemed to the writer that the biotite schists lie above the Keewatin greenstones, and that the Seine series lying on the greenstone give the following succession:

Keweenawan	8. Diabase dikes
Algoman	7. Granite stocks
Seine series	6. Biotite schist (upper sediments)
	5. Green slaty sediment (gold ore horizon)
	4. Conglomerate
	3. Arkosite
	2. Conglomerate (bottom of sediments)
(Unconformity and probable intrusives)	
Keewatin	1. Greenstone complex

The green slaty rocks are enough like the greenstones below, and like certain shear zones, to furnish the basis of the disagreement as to the age of the rocks containing the ore.[7] At the best exposures the green rock grades into the green matrix of a conglomerate (number 4 of the tabular section), so that the sediment is clearly above the recognized Seine conglomerate.[8] The ore is no doubt genetically related to the Algoman intrusives. Less developed prospects lie in other members of the Seine series.

The deposit has been described as a "segregated vein," less regular than a "true fissure vein"; a series of overlapping lenses of quartz, conforming to the bedding and foliation. The rock between lenses is also impregnated with quartz and ore so that it

[7] Lawson, A. C.: The Archean geology of Rainy Lake re-studied. Can. Geol. Surv. Mem. 40, 1913. Grout, F. F.: The Coutchiching problem. Geol. Soc. Am. Bull. vol. 36, pp. 351–364, 1925. Merritt, P. L.: Seine-Coutchiching problem. Geol. Soc. Am. Bull. vol. 45, pp. 333–374, 1934.

[8] The green rock with ore was assigned to the Keewatin in earlier reports.

was taken out with the lenses. The zones of ore are of variable width and none has been traced far under the drift, swamps and lakes, but the vein or zone of the Little American mine is said to appear for a distance of nearly three miles on the islands east and west of the mine, and on the south shore of the lake in Sec. 26. Nothing is safely predicted as to its size and richness, however. The ore is described as occupying a faulted zone with some slickensides, but very uncertain displacement.

At the time of the report the minerals recognized in the veins were quartz, pyrite, gold and a chloritic mineral probably from the walls. A petrographic examination shows tourmaline and ankerite also (Figs. 2 and 5), so that the ore is much like the hypothermal ores of several producing gold mines of Ontario.[9] The quartz is sutured and fractured, some of the tourmaline being later than the main quartz veins. The large size of the gas bubbles in the abundant liquid inclusions in the quartz supports the suggestion of a hypothermal origin. The rustiness of the outcrop is not so much from sulphides as from the ferruginous carbonate, mostly ankerite.

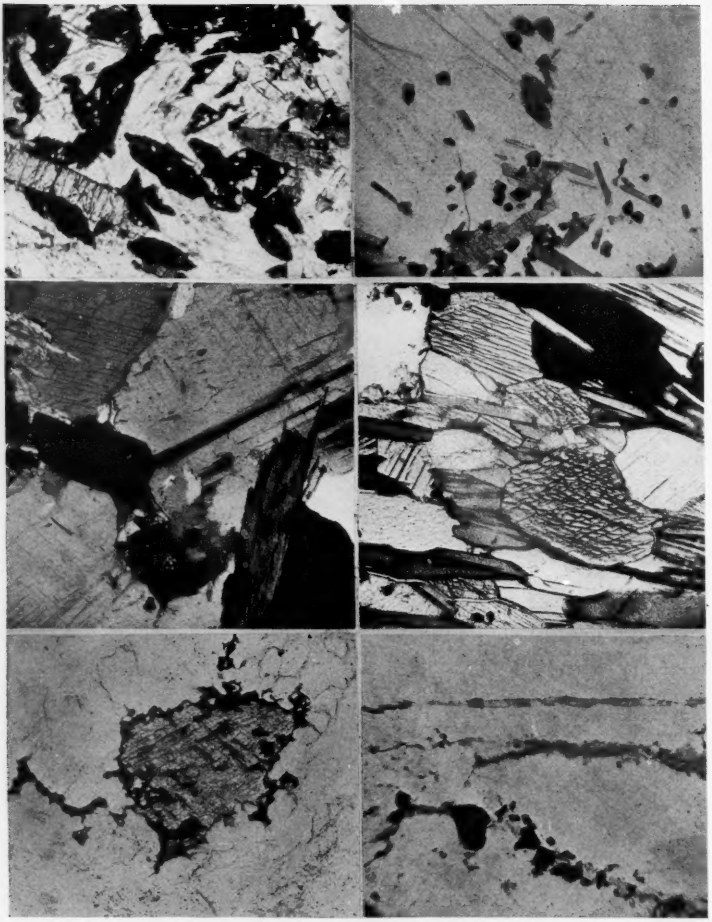
Since the Little American mine was the first gold mine in the district to come into production,[10] it is noteworthy that on the Ontario side of the boundary something over a million dollars worth of gold has been mined in the Rainy Lake district, mostly from hypothermal vein zones of this character.

OTHER PROSPECTS OF THE HYPOTHERMAL TYPE.

On Rainy Lake.—Near the Little American mine there is a series of less explored prospects of similar quartz veins and overlapping lenses. The "Lyle mine" at the north tip of Dryweed island (near the center of the SE¼ of Sec. 23, T. 71 N., R. 22 W.) is said to have had a 100-foot shaft in 1895. Quartz, ferrodolomite, tourmaline and pyrite form most of the vein and there

[9] Compare the mineral association of gold at Porcupine and Deloro. W. Lindgren, Mineral Deposits, 3rd ed., pp. 750 and 637, 1928. See also J. B. Tyrrell, pre-Cambrian gold fields of Central Canada: Roy. Soc. Can. Proc. and Trans., 3d ser., vol. 9, pp. 89–118, 1915–16.

[10] Coleman, A. P.: *Op. cit.*, 1895, p. 41.



FIGS. 1–6. Thin sections of specimens from gold prospects of Minnesota. Nos. 1–4, × 40; No. 5, × 36; No. 6, × 15.

FIG. 1. Tourmaline and specularite in carbonate vein, Rainy Lake.
FIG. 2. Quartz and tourmaline vein, Vermilion Lake.

is a little feldspar and apatite, perhaps from the chlorite schist wall. The wall rock is like that of the Little American, but it is at a somewhat lower horizon in the Seine sediments. The tourmaline was recognized here by the early prospectors.[11] The values must have been low and the work was soon abandoned.

On Bushy Head Islet, Sec. 26, T. 71 N., R. 22 W., a quartz vein with later ankerite and muscovite crosses a mineralized and contorted schist; all three were prospected. The schist, some largely chlorite and sericite, contains introduced ankerite, tourmaline specularite and pyrite (Fig. 1). The specularite forms rosettes and lenticular crystals up to a millimeter or two in size. The tourmaline also is coarse and euhedral in the carbonate and in the schist.

Similar veins, less mineralized, are opened on Cranberry Islet, and on Steamboat Islet on the east and west sides of Sec. 28, T. 71 N., R. 21 W., and on the east end of Grassy Island.

Small veins near by in the Seine arkosite or porphyry (sericite schist) and in the biotite schist have shown less gold than those in the sheared green slaty zone. The veins that have produced gold on the Canadian side, however, occur in several different country rocks.

On Vermilion and Mesabi Ranges.—In 1865 a gold rush to Vermilion Lake was started by the finding and report of gold and silver by state geologist Eames and others. Shafts were sunk and several stamp mills were built, the machinery having been packed in on the backs of Indian packers. The same land subsequently found valuable for iron ore was taken for gold claims. By 1867 it was clear that the ore was too lean, and the country became deserted, iron deposits and all.[12]

[11] Coleman, A. P.: *Op. cit.*, 1896, p. 63.

[12] Winchell, N. H.: *Op. cit.*, 23d Ann. Rept., p. 146, 1895.

FIG. 3. Biotite granite with sulphides (black in picture), Vermilion River.

FIG. 4. Phlogopite actinolite schist with pyrrhotite (black in picture), Vermilion River.

FIG. 5. Ankerite oxidizing to hematite in quartz vein, Rainy Lake.

FIG. 6. Ankerite and pyrite in late veinlets crossing quartz, Vermilion Lake.

The veins prospected are scattered at a number of points around the lake, partly in Keewatin greenstone and partly in the Ogishke-Knife Lake sediments overlying the greenstones. Evidently several prospects found the mineralized walls, both greenstone and porphyry, at least as promising as the veins. The veins are mostly quartz, with ankerite, pyrite, chalcopyrite (possibly some chalcocite), with some feldspar, rutile and fragments of chlorite and micaceous wall rocks.[13] The mineralization is partly later than the quartz (Fig. 6). Two or more of the veins carry tourmaline, and probably all are hypothermal. These are the prospects on Gold Island, at the southeast corner of T. 63 N., R. 17 W.; and a mile west of the end of Birch Point, near center of NW¼ Sec. 9, T. 62 N., R. 16 W. (Fig. 2).

At Pipestone Rapids, T. 64 N., R. 11 W., the water falls over a quartz vein which is hypothermal. It was known from the early prospecting[14] that it had tourmaline, pyrite and a copper stain, but the assays must have been low, because little prospecting was done.

At Ely, west of the southwest bay of Long Lake is a large persistent vein that is probably of a similar origin. It extends through the SW¼ of SW¼ Sec. 30, T. 63 N., R. 12 W., and over into Sec. 25. The quartz vein is large and accompanies a granite dike, but is mineralized only locally with sulphides of copper, lead and zinc. The outcrop is rusty and copper stained at these places and assays showed variable amounts of gold.[15] Near Fernberg Lookout, east of Ely, a quartz vein is rusty as if mineralized, but has no other minerals to suggest its origin or value.

At Eagle Nest Lake a vein on the west side is probably similar.[16] West of Tower some rock about 600 feet southwest of the east quarter post of Sec. 6, T. 62 N., R. 16 W., is mineralized with pyrite, tourmaline and carbonate. At the "North American

[13] Winchell, H. V.: *Op. cit.*, Final Rept., vol. 5, nos. 395–428; in a composite sample taken by Survey men in 1891, no gold was found.

[14] Minn. Geol. and Nat. Hist. Surv., vol. 4, plate AA, and vol. 5, p. 330, no. 352.

[15] *Idem*, vol. 4, p. 258, and vol. 5, p. 842.

[16] *Idem*, vol. 5, p. 732.

Mine" south of Tower Junction, the dump of the supposed ore is largely porphyry, but includes some vein matter of quartz, pyrite, carbonate and the fragments of walls with albite, actinolite and chlorite. The large gas bubbles of the liquid inclusions suggest that these veins also are hypothermal.

Dr. J. W. Gruner collected some rocks near a prospect in the Virginia "Horn," showing rhyolite porphyry, and metamorphic rocks probably older than the porphyry, partly greenstone and partly fragmental rocks. The porphyry and other rocks are mineralized and crossed by small veins of quartz, carbonate and albite. The carbonate and feldspar are more abundant at the walls and within the walls, and quartz is more abundant in the centers of veins. Pyrite and probably gold may be related to this introduction but more have been noted in the wall rock thin sections than in the veins. Much of the carbonate is oxidized as if highly ferruginous originally. Grains of gold are visible but no large body is exposed and not much work has been done.

The veins of Lake of the Woods gold prospects are hypothermal but none have been reported on the Minnesota shore of the lake.

VEINS OF OTHER KINDS.

Two veins prospected for silver in northeastern Minnesota were reported to contain gold also. They lie in the Rove slate area which has had large silver production on the Canadian side of the boundary. On McFarland Lake, Sec. 6, T. 64 N., R. 3 E., near a portage that runs north from the west end of the lake, is a breccia zone between diabase and slate, cemented by quartz and carbonate with some pyrite. The old "Spalding Mine" in the same slate formation opened more definite veins, south of the east end of Lake Miranda in Sec. 5, T. 64 N., R. 2 E. These are probably epithermal [17] or mesothermal [18] veins and recent thin sections show no more than was known in the old days.

[17] Minn. Geol. and Nat. Hist. Surv., 16th Ann. Rept., p. 284, 1888; Bull. 24, pp. 61 and 82–84, 1933.

[18] Lindgren, W.: Mineral Deposits, 3d ed., pp. 683–692, 1928.

Quartz veins of uncertain character were prospected also in central Minnesota.[19]

CONTACT DEPOSITS.

At Kelliher, Beltrami County, SW¼ Sec. 31, T. 152 N., R. 30 W., Dr. Ira S. Allison collected from a gold prospect specimens indicating contact mineralization of a greenstone by a trachite porphyry. The prospect is at the west end of a series of small outcrops in a belt running a little north of east. The mineralized zone, a number of feet wide, seems to be greenstone schist modified by contact action and small replacement veins so that it is now largely brown garnet, actinolite, chlorite, epidote, carbonate, and pyrite. Much of the garnet is birefringent and it is probable that metamorphism, before the contact action, had made the greenstone largely over into chlorite, carbonate, leucoxene and other alteration products, some of which remain as patches and streaks in the ore.

IGNEOUS AND PEGMATITIC SEGREGATIONS.

In Saganaga Lake a granite mass 15 by 25 miles has locally on "Gold Island" in Sec. 14, T. 66 N., R. 5 W., a fluorite zone with some fluorite pegmatite and quartz masses, bearing gold. The purple fluorite in the pegmatite seems to be primary, as is also some of that in the granite, but some is late and crosses the granite feldspar in tiny veinlets. The red feldspars are dusty with kaolinite and have some perthitic and chess-board structure indicating a history of recrystallization or replacement. The dark minerals are almost wholly changed to carbonate and near the surface these are weathered to rusty spots suggesting that the carbonate was ankerite. The gold was probably related to a deposition of smoky quartz somewhat later than the fluorite pegmatite.

Two early discovered veins in the Minnesota River valley were prospected for gold. One at Granite Falls, 1500 paces north of

[19] Near Watab, a quartz vein between two igneous rocks, Minn. Geol. and Nat. Hist. Surv., Final Rept., vol. 2, p. 436, 1888; and in Carlton County a series of quartz and pyrite veins in slate, vol. 4, p. 23, 1899.

the southeast corner of Sec. 4, T. 115 N., R. 39 W., is mainly quartz cutting a garnetiferous gabbro gneiss. Recrystallization near the vein has made the wall rock quite massive.[20] Thin sections show that the vein carries andesine and antiperthite, such as are found in the wall rock, but the texture indicates a pegmatitic relation to the wall rather than a modification of wall rock fragments. Pyrite is the only noteworthy metallic mineral. A similar vein was explored two and a half miles north of Delhi, in the northwest quarter of Sec. 4, T. 113 N., R. 36 W., and from there northwest a mile or more.[21] The quartz of the vein is shattered and full of strain shadows, and has associated some albite ($Ab_{95}An_5$). It crosses a basic rock that has the petrographic character of a hornfels, but is not exposed well enough to show its origin. These two veins are probably pegmatitic but may have later hypothermal quartz added and they are old enough to have suffered considerable deformation.

Prospect pits in Secs. 35 and 36, T. 64 N., R. 5 E., in the Rove slate area, were opened for nickel and copper but are said to carry some values in gold also. The main ore is a chalcopyrite-pyrrhotite segregation in a diabase intrusive, with local replacements at high temperatures forming masses of xonotlite, prehnite and sulphide. Thin and polished sections of the diabase near the masses also show sulphides widely disseminated in the rock. They include pyrrhotite, chalcopyrite, with subordinate cubanite, pentlandite and violarite. These in the fresh diabase seem as clearly primary as the augite, magnetite, olivine and biotite, though all these are later than the labradorite laths. The more massive replacement ores are perhaps hydrothermal rearrangements of the material of the same magma source as the primary sulphides.[22]

Near Indus, in Sec. 4, T. 159 N., R. 25 W., Dr. J. W. Gruner sampled a gold prospect in mineralized diabase and greenstone. The pyritic material is introduced and disseminated in the greenstone but is not accompanied in the diabase by any considerable

[20] U. S. Geol. Surv. Bull. 150, pp. 282–283, 1898.

[21] Minn. Geol. and Nat. Hist. Surv., 23d Ann. Rept., pp. 102–3, 1895.

[22] Schwartz, G. M.: A sulphide diabase from Cook County, Minnesota. ECON. GEOL., vol. 20, pp. 261–265, 1925.

hydrothermal attack. It may be primary pyrrhotite segregated a little later than the crystallization of the early silicates.

It is not likely that the porphyry mentioned above as part of the material mined at the North American mine is a magmatic segregation for it was mineralized after the solidification of the porphyry.

MIGMATITES AND REPLACEMENTS.

The latest elaborate exploration for gold in the state is known as the Vermilion River Mines. The property lies along the banks of Vermilion River in Sec. 36, T. 67 N., R. 18 W. The work has been rather extensive and a shaft has been sunk deep enough to run off two levels and cross cuts. The district is in the midst of the largest batholith of the state, the Vermilion granite, but at a place where schist inclusions and possibly roof pendants are abundant, and where pegmatites and quartz veins complicate the structure. The ore has proved so lean and irregular that work has been abandoned. It consists largely of the several rocks just mentioned, with visible pyrrhotite, chalcopyrite and pyrite. These may be primary in the pegmatite, aplite, silexite and quartz veins, but are introduced into the biotite schist of sedimentary origin and into the gneisses formed by lit-by-lit injection of such schist. One mineralized schist specimen consists largely of tremolite and pale biotite, and may be an altered greenstone rather than a sediment. Most of the material is much the same as has been described in reports on the batholith,[23] and the granite is very light pink in color, except where contaminated by schist. Where injection has been so extensive that half or more of the gneiss is igneous material the sulphides seem to be primary as they are in the pegmatite and aplite, leaving a little uncertainty whether they were constituents of the schist before injection, or later additions and replacements. Several specimens from underground, however, show pyrrhotite and pyrite in pegmatite and aplite where there is no sign of contamination and it is therefore believed that

[23] Grout, F. F.: Geology and magnetite deposits of northern St. Louis County, Minnesota. Minn. Geol. Surv. Bull. 21, 1926.

most of the mineralization is related to injection (Figs. 3 and 4). Much of the pyrrhotite here is highly magnetic.

The prolonged active exploration has stimulated some prospecting at several similar outcrops in the district. Specimens have been examined from Sec. 33, T. 66 N., R. 17 W., and from Sec. 3, T. 65 N., R. 17 W. They show sulphides in migmatite resulting from injection of mica schist.

These prospects may be classed as hypothermal deposits because of the abundant pyrrhotite, but some are aplite and pegmatite, and they are notably different from the tourmaline veins. They seem to be less promising.

MISCELLANEOUS.

Several flurries of interest have been aroused by other reports of gold, which had less foundation than these described. Near Cook, a basic intrusive with half-inch biotite flakes was assayed repeatedly because the weathered biotite was yellow and looked metallic. Many quartz veins and carbonate zones in the pre-Cambrian have been sampled by prospectors and geologists, but few assays showed gold and these only in local bunches rather than in extensive deposits. Even as lean a formation as the St. Peter sandstone near Fort Snelling has been the subject of wild rumors, though the talk of gold must have been based on an error. The old Survey reports mentioned gold washed from the drift at several places in the state, but made it clear that most of these deposits are local pockets of no importance.

SUMMARY.

The Little American mine, first producing gold mine of the Rainy Lake district, was abandoned as unprofitable before 1900. The deposit is of hypothermal origin, a tourmaline-ankerite-pyrite quartz vein zone. Similar veins are scattered over a rather extensive area around the Vermilion batholith. There is no evident geologic reason why the stocks and small intrusives near the borders of the mass should not be favorable for gold

prospects, but explorations since 1865 have not revealed any others of value. A petrographic study of other prospects shows a variety of types, mesothermal veins, contact deposits, segregations, pegmatites and deep seated replacements; some other formations have been explored because of baseless rumors or erroneous reports from assayers.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.
Dec. 1936.

GENESIS OF SOME SULPHUR DEPOSITS OF THE U. S. S. R.

P. M. MURZAIEV.

CONTENTS.

Introduction 69
Description of Deposits 70
Knibyshev 72
Sukeievo 86
Chekur-Koyash 87
Kazbek 90
Gumur 92
Kamchatka 93
Genesis of Bedded Sulphur Deposits 94
Methods of Reduction of Sulphates 95
Is the Sulphur Syngenetic? 99
Conclusion 102

INTRODUCTION.

THE genesis of bedded sulphur deposits has so far been a controversial problem. According to some authors, sulphur was deposited in lagoons contemporaneously with the enclosing rock, whereas others believe that it was either injected therein or was formed later through replacement of gypsum strata.

This paper contains the description of six sulphur deposits of the U. S. S. R., three of which are bedded, and three of which are epigenetic-volcanic. Comparison of their structural variations has led the writer to suggest that their origin was not the same. Experimental evidence favors a biochemical process of the reduction of sulphates in nature.

The writer is deeply indebted to professors A. N. Zavaritzki, L. M. Miropolski, and A. A. Florenski for having kindly put their material at his disposal, and to Professor D. I. Mushketov for his encouragement and mediation as an Associate Editor of this journal.

DESCRIPTION OF DEPOSITS.

Sulphur Deposits Near Knibyshev.

These deposits occur in many localities, but mainly on the left bank of the Volga (Fig. 1). The description of the deposit at Alexeievka furnishes the basis of the writer's deductions as to the genesis of all the deposits of the region, since other localities are little explored and furnish no available data.

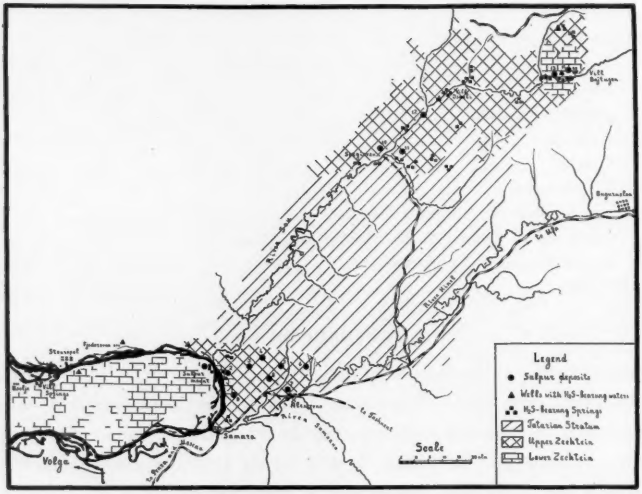


FIG. 1. Schematic geologic map of sulphur deposits near Knibyshev (after N. S. Obukhovski). 1. Sernaia Gora. 2. Krasnaia Clinka. 3. Novo-Semeykinskoie. 4. Vodino. 5. Kazachi-Ovrag. 6. Kamenny-Ovrag. 7. Alexeievka. 8. Petrova-Dubrova. 9. Sorokiny Khutora. 10. Sernovodsk. 12. Nijniaia Oboshnia. 13. Kamyshlin. 14. Baytugan.

The area of distribution of sulphur is a hilled plain with scattered woodlands. Geologically, it is bordered on the north by a fault [1] that extends along the northern extremity of the Giguli mountains, the Volga, and the river Sok. On the west, rocks of the Conchiferous horizon disappearing below Tartarian sedi-

[1] Pavlov, A.: Samarskaia Luka and the Giguli. Mém. Com. Géol., t. II, no. 5.

ments, reappear near the city of Sernovodsk. On the south, a fault can be traced along the Samarka river. The eastern limit is the deposit of Sernaia Gora.

The area described consists of Conchiferous rocks in the Kazan group of the Upper Permian (Upper Zechstein). Their total thickness is about 100 meters. These rocks are underlain by those of the Spirifer horizon (Lower Zechstein), Kazan group, outcropping on the periphery (Fig. 1) of the area of Conchiferous rocks.

A section of the Alexeievka deposit (Fig. 2) gives an approximate idea of the geological structure of the whole country,

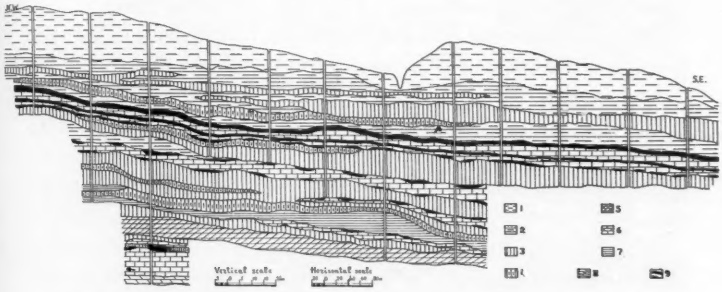


FIG. 2. Section of the Alexeievka sulphur deposit (after V. A. Izergin). 1. Tartarian deposits. 2. Interstratified beds of clays and marls. 3. Gypsum. 4. Marls. 5. Anhydrite. 6. Bituminous dolomitic limestone. 7. Beds of green marly clays, thinly interbedded with marls, gypsum, and limestones. 8. Dolomite. 9. Sulphur-bearing strata. Vertical lines indicate borings.

showing mainly dolomitic limestones, gypsum, and marly clays interbedded. Transitions between them are mostly gradual and occur as alternating thin laminations (0.5 cm. to 3 cm. in thickness) of both rocks. These rocks are all of lagoonal origin being sediments of a shallow and probably isolated Permian sea.[2] The deposits are overlain in places by rocks of the Tartarian (Upper Permian) represented by marly clays, limestones, and red and

[2] Nalivkin, D. V.: Textbook of Historical Geology. 1932.

gray sandstones. The sedimentary rocks that dip gently southeastward are in places considerably karsted.

The strata have mostly short outcrops and commonly wedge out (Fig. 2); this is particularly noticeable in the Vodino deposit. Interpolation of strata in sections 50 m. apart is difficult.

Knibyshev Deposits.

The Alexeievka deposit has been disclosed by shafts and galleries to a depth of 20 m. and boreholes have reached a depth of 120 m. The two sulphur-bearing layers formerly mined have been explored sufficiently to indicate their structure. Other horizons (about ten in number) are known only from cores.

Figure 2 shows the geological structure of the deposit, and the location of the sulphur-bearing strata, which occur in bituminous dolomitic limestones, particularly in their upper parts. Sulphur is rare in gypsum and marly clays. All sulphur-bearing strata are conformable to the stratification. Nos. 1 and 2 (Fig. 2) are continuous throughout the whole area; the others are lenticular.

The upper sulphur-bearing horizon (Fig. 2) exceeds the others in thickness, averaging 1 m. and varying from 18 to 228 cm. As shown in Fig. 2, it lies in the upper part of a stratum of dolomitic limestone, and consists (Figs. 3 and 4) of thin (5 to 15 cm.) laminations of a mixture of sulphur and calcite enclosed in biuminous dolomitic limestone. Such sulphur inclusions may be continuous for hundreds of meters or may occur in short lenses. Bituminous sulphur predominates over pure sulphur. The latter is developed in the upper part of the horizon (Fig. 3), and grades upward into barren rock. In laminations of sulphur and calcite, secondary gypsum replaces sulphur (Fig. 4) in the upper parts of the lenses. In the upper parts of the horizon are laminations of secondary selenite-like gypsum. In such places the dolomitic limestone is disintegrated, fissured, and crumbles readily, whereas in the lower parts it is a dense compact rock (Fig. 4).

The upper sulphur-bearing horizon gradually passes downward into dolomitic limestone, with transitions of vuggy limestone occupied by calcite crystals or liquid bitumen. Rarely, pure

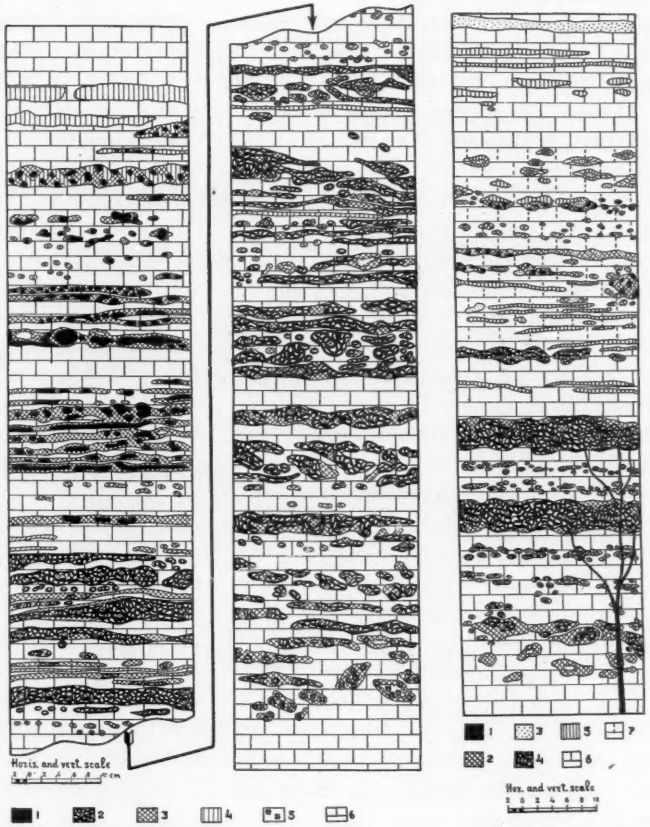


FIG. 3. Alexeievka, part of first horizon; FIG. 4, part of first sulphur horizon. Sulphur, 1; bituminous sulphur, 2 (Fig. 3), 4 (Fig. 4); calcite, 3 (Fig. 3), 2 (Fig. 4); selenite and selenite gypsum, 4 (Fig. 3), 5 (Fig. 4); fine grained gypsum, 3 (Fig. 4); bitumen in calcite, 5 (Fig. 3); bituminous dolomitic limestone 6, same fractured, 7. Figure 4 shows forms of sulphur in vertical cracks.

or bituminous sulphur occurs in vertical cracks in the upper limestone of the first sulphur zone and in the dolomitic limestone between the first and the second sulphur zone. The latter is unaccompanied by calcite but occurs in crystals or crusts that may fill the fissures, which show no evidence of corrosion. At one place (Fig. 4) the sulphur resembles the branches of a tree that unite into a vertical trunk.

The second sulphur-bearing horizon lies 4 to 5 meters below the first, in the same 7-meter bed of bituminous dolomitic limestone, and 2 to 2.25 m. above its base. It extends throughout the entire area, and thickens westward, beyond the borders of the area. Its average thickness is 32 cm., varying from 0 to 72 cm. The second horizon differs from the first in that it is separated from the enclosing rock by thin (10 cm.) laminations of black bituminous colloidal clay that includes concretions of sulphur and lutecite (Fig. 5).

This horizon consists of laminæ of sulphur and calcite enclosed in limestone, in places attaining 10 cm. in thickness. Much lutecite and celestite are admixed with sulphur. This horizon contains many cavities whose walls are coated with crystals of calcite, celestite and sulphur.

The remaining sulphur-bearing horizons are not extensive and few have been cut by bore-holes. They are either single interbedded lenses or lenticular laminæ (Fig. 2). The distribution of the sulphur is the same as in the two horizons already described.

From the deeper parts of the deposit, H_2S and CO_2 rise to the surface along cracks in the rock, and in springs.

The sulphur deposit at Kazachi-Ovrag is situated 5 km. north of Alexeievka (Fig. 1). Sulphur is found in only two-thirds of the artificial exposures, and is associated with the same rocks of the Conchiferous horizon. In the lower part of the exposures there is bituminous cherty limestone overlain by a 30 cm. limestone bed that contains rounded concretions of sulphur and calcite. The sulphur is either bituminous or pure. Above this are alternating layers of dolomitic limestone and sulphur with calcite which near the surface contains more or less gypsum, probably

formed by oxidation of sulphur. This is overlain by 50 cm. of fine-grained gypsum. The total thickness of the alternating layers is 1 m., each lamination being 3 to 10 cm. thick.

The deposit near Vodino is situated 15 km. north of Alexeievka (Fig. 1). Sulphur is exposed in galleries and bore-holes and is associated with layers of dolomitic bituminous limestone and greenish marly-clay. Five or six sulphur-bearing horizons have

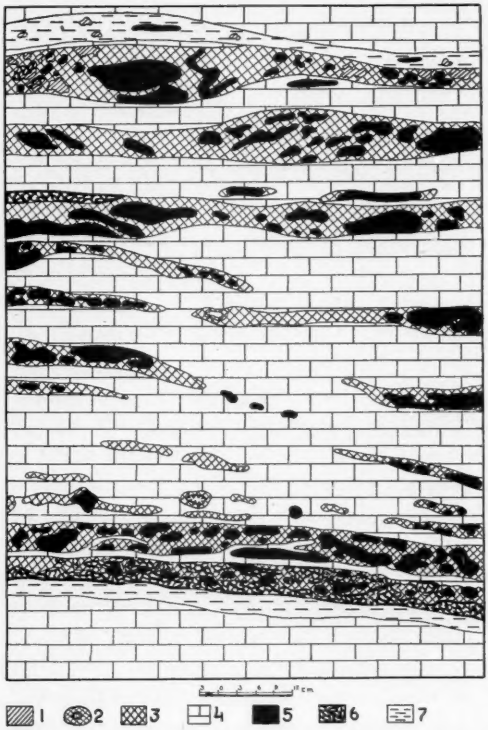


FIG. 5. Sketch of a part of the second sulphur-bearing horizon at Alexeievka. 1. Lutecite. 2. Cavities with calcite crystals. 3. Calcite. 4. Bituminous dolomitic limestone. 5. Pure sulphur. 6. Bituminous sulphur. 7. Black bituminous colloidal clay.

been observed to a depth of 45 m. Their strike-length is not great (less than 50 m.) and they wedge out rapidly. Sulphur generally occurs in the form of concretions with calcite and gypsum, and as lenticular inclusions in limestone and marly-clays. Such concretions sometimes reach 50 cm. in diameter and consist of pure sulphur without admixtures of calcite and gypsum. Calcite is found in the marly-clays and dolomitic limestones that enclose the concretions. The latter are in places separated from the enclosing marly-clay by a thin coating of the same clay 1 to 2 cm. thick, enriched with bitumen. In other places, the center of the concretion consists of sulphur only, surrounded by a mixture of sulphur, or of gypsum and calcite, the content of bitumen increasing towards the periphery. The concretions are either irregularly distributed along a definite horizon, or are disseminated within certain strata. In the dolomitic bituminous limestone, there are some cavities filled with viscous, semi-liquid bitumen, the walls of which are coated with well developed crystals of sulphur. Some finely divided sulphur occurs in the dolomitic limestone.

Interesting laminæ of selenite-like gypsum lie adjacent to layers of pure sulphur. They may be sinuous, and the adjacent sulphur conforms to the sinuosity of the gypsum.

The Sernaia Gora deposit is situated on the opposite (right) bank of the Volga, on the eastern margin of the Giguli mountains. It has been known since the end of the XVIIth century, when it was worked for sulphur under Peter the Great. On the banks of the Volga, in the neighborhood of the deposit, huge jars with unusual orifices have been discovered in which sulphur was melted. The plateau-like summit is covered with ancient workings that reveal an upper layer of fine-grained gypsum over 5 m. thick, underlain by compact bituminous dolomitic limestone. In the limestone are nodules of sulphur bordered by calcite and gypsum, measuring 5 to 20 cm. in diameter. Between the two beds is a gypsum lamina 2 cm. in thickness with small irregular inclusions of sulphur. In larger accumulations, sulphur, calcite, gypsum, and celestite are associated together.

Rocks and Minerals of the Knibyshev Deposits.—Bituminous dolomitic limestone is common in this district. Pure limestones and dolomitic ones free from bitumen are lacking; dolomites are rare, but have been struck in the lower part of the Alexeievka deposit (Fig. 2). The content of bitumen in the dolomitic limestones varies from 0.2 to 5 per cent., and MgO from 6 to 20 per cent. They contain from 1 to 15 per cent. of silica, the percentage increasing towards the bottom of the layer. A small amount of NaCl (about 0.01 per cent.) is always present, as well as a small amount of free sulphur (about 2 per cent.) dispersed throughout the rock.

Macroscopically, bituminous dolomitic limestone appears as a compact homogeneous dark rock with more or less distinct fine lamination. There is also some spotted dolomitic limestone, which under the microscope proves to consist of fine grains of dolomite and calcite, most of which are structureless oölites (Fig. 5).

In finely laminated rocks, single layers differ from each other in content of calcite and bitumen and in size of grains. Bitumen impregnates the rock, filling the interstices between the grains in the form of films and flake-like accumulations. Bitumen is more common in fine-grained laminæ, whereas an adjacent more coarsely grained layer, not separated from the former may contain little or none. At places, two contiguous laminæ, identical in structure, differ by the occurrence of bitumen in one and the total lack of it in the other. Such a feature points to a syngenetic origin. The structure of the rock, the occurrence of dolomitic oölites in gypsum grains, the fine interstratification of gypsum with dolomitic limestone, the absence of fossils, and the fingering-out of layers, point to a lagoonal origin of the beds by chemical precipitation.

Gypsum is widely distributed in sediments of the Conchiferous horizon. Morphologically, four varieties may be distinguished: (1) fine-grained gypsum (alabaster or rock-gypsum); (2) selenite-like or fibrous gypsum (irregularly fibrous); (3) selenite (regularly fibrous gypsum); (4) spar gypsum (Mary's glass).

The fine-grained gypsum generally occurs in the form of seams

or lenses up to 8 m. thick, but along the cracks, it grades into selenite-like gypsum, which also forms surface layers. Selenite occurs only in thin laminæ (2 to 20 mm.) and in veinlets, and is always secondary after grained gypsum. Spar gypsum forms neither laminæ nor veinlets, but generally fills cavities in the rock, always in close association with sulphur. Such crystals commonly include sulphur; in places they may entirely fill the cavities previously occupied by sulphur.

The microscope reveals residual grains of anhydrite in crystals of fine-grained and selenite-like gypsum. A layer of anhydrite has been discovered at a depth of 90 m. in the Alexeievka deposit (Fig. 2). It may be stated that all the varieties of gypsum of the Knibyshev deposits are secondary formations of three kinds. The main mass of stratified gypsums (fine-grained and selenite-like) is due to hydration of anhydrite. All of the spar gypsum, part of the selenite-like gypsum, and some of the fine-grained, originated during oxidation of sulphur. Finally, selenite and part of the selenite-like gypsum owe their origin to recrystallization of gypsum by surface waters. The latter process is most distinctly shown in the Sernaia Gora deposit; in exposures of thick (5 to 10 m.) layers of fine-grained gypsum, veinlets of selenite-like gypsum cross the layer in every direction. The common distribution of selenite veinlets is shown in Figs. 3 and 4. It has been observed that fine-grained gypsum which later grades into the selenite-like gypsum forms during the hydration of anhydrite. Krotov [3] observed gradual transition from anhydrite through the same stages to spar gypsum.

Anhydrite was struck by bore-holes in the Alexeievka deposit, at a depth of about 90 m. It occurs in a layer averaging 10 to 12 m. in thickness (Fig. 2), which is traversed by a multitude of gypsum veinlets. Newland [4] places the lower limit of stability of gypsum at a depth of 200 to 300 ft., Udden [5] at 850 ft., Gold-

[3] Krotov, B. P.: On gypsum and anhydrite in the upper horizon of Kazan formation near the city of Kazan. Bull. Soc. Russe Minér., sér. 2, 1926, p. 52.

[4] Newland, D. H.: Geology of gypsum and anhydrite. Econ. Geol., vol. 16, pp. 393–404, 1921.

[5] Udden, J. A.: Laminated anhydrite in Texas. Geol. Soc. Am. Bull., vol. 35, p. 348, 1924.

man [6] at a few hundred feet, and Rogers [7] at 400 m. The lower limit of Alexeievka gypsum is at 300 to 350 ft. (90 to 100 m.). At the surface, no anhydrite has been observed. In shafts, at a depth of 10 to 15 m., rare single nodules of anhydrite have been found, coated on the periphery with gypsum and enclosed within dolomitic bituminous limestone. Microscopically anhydrite appears as numerous grains that exhibit flow structure with which are aligned dolomite oölites. Some inclusions of pyrite occur. Veinlets of fine-grained and selenite-like gypsum are common.

Calcite is found: (1) as a component of dolomitic limestones; (2) as independent laminations in dolomitic limestones; (3) as concretions of granular calcite (about 3 cm. in diameter) constituting layers interbedded with the same rocks (Kazachi-Ovrag); (4) as a granular admixture with sulphur (Figs. 3–5); (5) in the form of small scalenhedrons coating the walls of cavities, with or without crystals of celestite and sulphur.

The first four represent calcite in its primary form, as it was segregated at the bottom of lagoons simultaneously with the enclosing rock. The last form is the result of recrystallization of the first four (Fig. 7).

Calcite invariably accompanies sulphur; sulphur lamina free from recrystallization and calcite, are unknown. Secondary processes, such as recrystallization and migration of sulphur, separate calcite from sulphur, and during oxidation of the latter, gypsum is formed, partly or entirely replacing calcite.

Sulphur is found pure and bituminous in the following forms: (1) finely disseminated in dolomitic limestone; (2) as laminations in bituminous dolomitic limestone admixed with calcite, or with lutecite (Figs. 3, 4, 5, 6); (3) as single, rounded, or lenticular accumulations of sulphur with calcite, (Figs. 3, 4, 5); (4) filling cavities (Fig. 7) either entirely, or in well developed crystals together with excellent crystals of calcite and celestite; (5) filling cracks in the rock (Fig. 4).

[6] Goldman, M. I.: Petrography of salt-dome cap-rocks. Am. Assoc. Petrol. Geol. Bull., vol. 9, no. 1, 1925.

[7] Rogers, A. F.: Occurrence and origin of gypsum and anhydrite of the Ludwig Mine, Lyon County, Nevada. Econ. Geol., vol. 7, pp. 185–189, 1912.

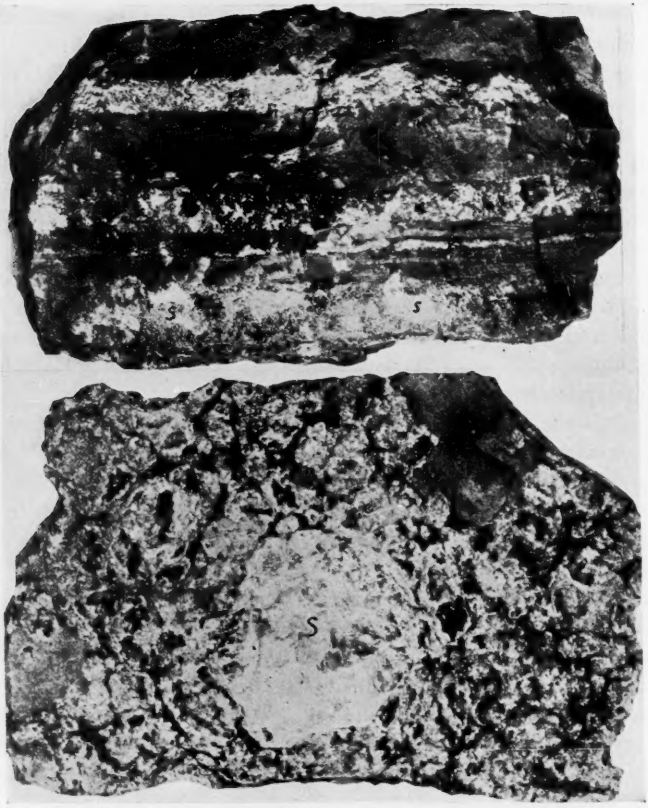


FIG. 6. Part of the first sulphur-bearing horizon, Alexeievka. Primary deposition of bituminous sulphur admixed with calcite. The latter also forms independent laminæ within the enclosing bituminous dolomitic limestone. *S*, fine mixture of sulphur and calcite. *K*, pure calcite laminæ. × ½.

FIG. 7. Section showing strongly recrystallized sulphur lamina. Second sulphur-bearing horizon, Alexeievka. Nat. size. Numerous nodules with fine crystals of calcite scalenohedrons coating their walls. Rare cavities entirely filled with pure, coarse-grained sulphur (*S*) and crystals of celestite (*C*). Large sulphur crystals here appear to have grown, as usual, at the expense of small ones. Partial evacuation of sulphur is probable here.

The first three forms represent primary deposition of sulphur, the fourth, the recrystallization of nodules, and the fifth, transportation and redeposition of sulphur.

Where concretions of sulphur with calcite bear no distinct traces of recrystallization, the calcite is always distinctly euhedral; the sulphur generally fills the spaces between the calcite grains (Fig. 8).

In places sulphur penetrates the calcite crystals or vice versa, or a pegmatitic structure results.[8] Calcite then shows higher crys-

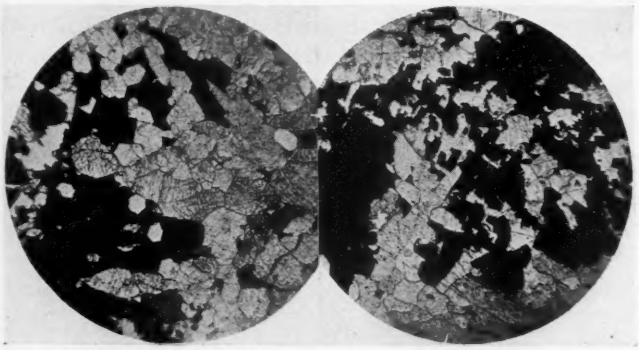


FIG. 8. Sulphur nodule with calcite, Alexeievka. Euhedral grains of calcite (light) and anhedral sulphur (dark). Some calcite grains within sulphur.

FIG. 9. Sulphur nodule with calcite, Alexeievka. "Pegmatite-like" intergrowth of sulphur (dark) and calcite (light) is seen.

tallizing p[illegible]wer than sulphur (Fig. 9), which indicates a simultaneous origin.

In primary beds sulphur is more bituminous than where recrystallization has occurred. Figure 3 shows the predominating

[8] Murzaiev, P. M.: Geologic-mineralogical studies of Adun-Chilone granitic massif in Transbaikalia. To appear in the Transactions of the Geol. Hydrol.-Geodet. Office. The writer draws a distinction between eugraphic pegmatite, with distinct graphic structure, and angraphic pegmatite, transitory from aplite, like pegmatite and the eugraphic form. Both of these types as well as others were observed by the writer in the said massif.

non-bituminous sulphur in the upper part of the sulphur-bearing horizon. Recrystallization is generally absent in compact layers of bituminous sulphur, but is common in lenticular laminations. Bituminous and pure sulphur seldom occur in the same layer.

Unlike many other deposits (Chekur-Koyash, Ghezyn-Bulak, near Krasnovodsk on the Caspian sea, and others) the Knibyshev sulphur deposits that occur in layers are more or less coarse-grained, distinctly crystalline, of deep amber-yellow color if free from bitumen or brownish-yellow if admixed with it. Sulphur crystals in cavities are elongated parallel to the *z*-axis and form in the order of decreasing frequency and of degree of development; always p 111, s 113, c 001, sometimes n 011. Parallel nodules are common. The shape of the crystals is generally similar to the forms figured by Goldschmidt.[9]

Celestite was observed in the following forms: (1) small (3 to 4 mm.) inclusions in sulphur bordered by a mixture of gypsum and calcite (Sernaia Gora); (2) Sparse grains associated with anhydrite grains within a mass of fine-grained gypsum from thick gypsum layers (Sernaia Gora); (3) Rare idiomorphic grains associated with calcite grains and admixed with sulphur. (Second sulphur-bearing horizon, Alexeievka.) (4) Large crystals coating a nodule of calcite. (Near Sorokiny Khutora.) (5) Well developed crystals in the interior of cavities of recrystallized areas of sulphur-bearing horizons, with crystals of calcite and sulphur (Fig. 7). (Second sulphur-bearing horizon, Alexeievka; Kazachi-Ovrag, Sorokiny Khutora, and others.)

The above list shows that in the first three cases, celestite is of primary deposition, being the result of chemical precipitation in cavities, together with anhydrite, which later passed into gypsum, and with sulphur and calcite, in which cases celestite is a product of recrystallization of primary layers.

The problem of the genesis of celestite in the Permian deposits of the U. S. S. R. has been considered by Fersman,[10] Krotov,[11]

[9] Goldschmidt, V.: Atlas der Krystallformen, bd. 8, taf. 18, fig. 97, and taf. 20, fig. 134, 1923.

[10] Fersman, A. E.: Geochemistry of Russia. Pt. I, p. 42, Leningrad.

[11] Krotov, B. P.: Dolomites, their origin, conditions of stability in the earth crust, etc. Tr. Soc. Natur. Univ. de Kazan, t. 50, pt. 6, 1925.

and Miropolski.[12] The former suggested that the accumulation of celestite was due to organisms that concentrated strontium sulphate dissolved in sea water. The two latter consider it a result of chemical precipitation in closed cavities, with anhydrite, which viewpoint is favored for the deposits under consideration. There are about seven types of celestite crystals, differing in elongation and in characteristic development of the sides. Fundamental and common to all types are the forms (in order of decreasing frequency and degree of development): y 122, n 120, o 100, p 210. The most widely distributed types approximate Figs. 221, 226, and 227 of Goldschmidt.[13]

Silica occurs in the form of: (1) lutecite, (2) flint, and (3) quartz and amethyst in close connection with lutecite (Sorokiny Khutora).

Lutecite is microscopically indistinguishable from chalcedony. It is generally associated with the upper sulphur layers and the upper layer of black colloidal clay in the second sulphur-bearing horizon at Alexeievka (Fig. 5).

Lutecite may be divided into forms I and II. The former occurs in independent horizontal laminations as lenticular accumulations or in close connection with sulphur, calcite, and other minerals. Lutecite II occurs mainly in vertical cracks in the rock where it is rarely associated with bitumen and quartz. Its occurrence and paragenesis indicate an epigenetic origin. It is a migratory form of silica.

Under the microscope, lutecite I appears: (1) as an aggregate of small regular spherolites, about 0.1 mm. in diameter; (2) as single large (1 mm.–1 cm.) spherolites, concretions in limestone; and (3) like lutecite II, as irregularly distributed radial concretions. In places, fibers of lutecite are at an angle to each other, as in microcline structure. Elongation of the fibers is positive. The angle of Ng to lutecite fiber varies from 10 to 30 degrees.

[12] Miropolski, L. M.: Contribution to the genesis of celestite in Permian deposits in Kazan district and in Northeast Russia. Tr. Soc. Natur. Univ. de Kazan, t. 51, pt. 4, 1926.

[13] *Op. cit.*

Agate-like zoning is observed in places. The immersion index of lutecite I and II is 1,533 $\pm$ 0.003.

Crystals of amethyst (Sorokiny Khutora) and grains of quartz occur at places in cavities within lutecite. All stages from lutecite to quartz, through quartz grains with indices of radial damping, have been observed.

Under the microscope, lutecite I is homogeneous in most cases. In places, single rhombohedrons of dolomite, grains of sulphur,

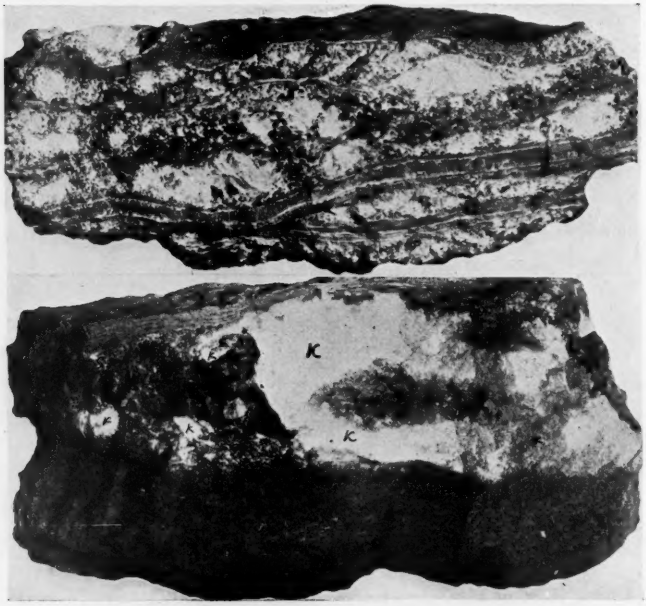


FIG. 10. Upper sulphur-bearing horizon, Alexeievka. Nat. size. Chaplet-like laminations of sulphur lenses (white) bordered with calcite (dark and light dots) in fine-laminated bituminous dolomitic limestone (gray stratified rock). Layers of limestone border the sulphur lenses.

FIG. 11. Section of the upper lamination of the second sulphur-bearing horizon, Alexeievka. Natural size. Sulphur (S) surrounded by calcite (K), with lutecite (L), part of sulphur lens replaced by secondary sparry gypsum (G).

and remains of radiolaria (Globigerina, textularia, etc.) occur. In the second sulphur-bearing horizon, lutecite I occurs in the same layer with sulphur, with complicated interrelations. It either borders the lenses of calcite, with sulphur, fills the spaces between them, encloses sulphur, or is enclosed in sulphur. In places, accumulations of lutecite are surrounded by calcite, separating it from the enclosing rock (Fig. 11).

Flint occurrs at Kazachi-Ovrag and elsewhere. Unlike lutecite, flint forms rounded and lenticular concretions from a few centimeters to twenty centimeters in diameter, that are irregularly dispersed within the dolomitic limestone. At Kazachi-Ovrag they are associated with a limestone layer underlying the sulphur-bearing horizons. Macroscopically, in color and structure, flint resembles the enclosing rock. No laminæ of limestone surrounding concretions of silex have been observed.

Under the microscope, flint appears to consist of an aggregate of carbonate of exactly the same structure as the enclosing dolomitic limestone, cemented by amorphous opaline silica. Some areas of opal show indistinct dark radial damping.

All stages from lutecite to quartz through quartz grains with indices of radial damping have been observed, demonstrating gradual transitions from opal to lutecite, and finally to quartz.

These structural features of silex seem to indicate that its origin is epigenetic. On the contrary lutecite I appears to be syngenetic, *i.e.* a result of precipitation of colloidal silica at the bottom of lagoons together with sulphur, calcite, clay, and limestone, and its later metamorphism.

Pyrite is rare in the Knibyshev deposits. It has been observed, rarely, in concretions in green clays of the upper part of the Alexeievka deposit; in the form of grains up to 1 cm. in anhydrite of the same deposit, and in the form of concretions bordered with sulphur and calcite in the third sulphur-bearing horizon at Alexeievka.

Sulphuretted hydrogen springs are widely distributed over the area of the deposits (Fig. 1), in most cases along established or supposed tectonic dislocations. In the area adjacent to the city

of Knibyshev they are rather low in H_2S, depositing no native sulphur at the surface. In the district of Serghievsk and Sernovodsk, springs are somewhat richer in H_2S, and, from lakes containing H_2S, small quantities of sulphur are deposited by oxidation. The content of H_2S varies from 2 to 20 mgr. per liter. The temperature of such waters is fairly constant throughout the year, at about 10 degrees C.

The fact that such springs are connected with fault lines is an indication of the deep-seated origin of the H_2S. Mine workings have shown that in the Alexeievka deposit at a depth exceeding 20 to 40 meters, all the rocks are impregnated with sulphuretted hydrogen.

The genesis of this hydrogen is unknown. It may be liberated gas [14] occluded by rocks during their formation; it may be a product of contemporary decomposition of sulphates by desulphurizing bacteria (see below); or both processes may take place simultaneously.

Sukeievo Deposit, near the City of Knibyshev.

These deposits cover a considerable area on the right bank of the Volga, downstream from the mouth of the Kama. The best sections are in the escarpment near the village of Sukeievo. Geologically the area consists of flat-lying dolomites, dolomitic limestones and gypsums of the Upper Permian Kazan formation, conformably overlain by sediments of the Tartarian formation. Sulphur is associated with the series of dolomites and dolomitic limestones bearing the local denomination "podlujnik," or "gray transitory series," belonging to the lower part of the Conchiferous horizon of the Kazan formation. According to Miropolski,[15] sulphur in this series does not occur in definite laminations of considerable extent, but is segregated in the form of concretions and nodules scattered within the "podlujnik" series. The thick-

[14] Vernadsky, V.: On sulphuretted hydrogen in limestones and dolomites. Bull. Ac. Sc., 1917, p. 1379.

[15] Miropolski, L. M.: Contribution to the genesis of sulphur deposits near the village of Sukeievo in the Tartarian Republic. In print.

ness of such areas varies from 1 to 12 m. According to Dravert,[16] there are four sulphur-bearing dolomite horizons. Sulphur is segregated:[15] (1) in dolomitic limestones in concretions with calcite and gypsum, jointly and separately; (2) along cracks in the rocks without accompanying minerals, in the form of flowers, crusts, and fillings; (3) bordering fossils; (4) in planes and cracks of silex concretions.

In concretions, sulphur and calcite are granular, but in cavities, crystals of sulphur, calcite, aragonite, celestite, and gypsum are found. Such cavities probably take the place of previous concretions. In places, pyrite and lutecite are observed.[17] Celestite is segregated either before or after sulphur; gypsum is always the latest mineral. Within siliceous concretions, the rarest form of segregation, sulphur forms crystals and crusts that coat quartz crystals. Sulphur may carry crystals of celestite, gypsum, and calcite. Selenite-like sulphur, of the same structure as that occurring at Chekur-Koyash (see below), is observed rarely.

The Sukeievo deposit differs in structure from those at Knibyshev in that compact continuous layers of sulphur are absent.

The Chekur-Koyash Sulphur Deposit in the Crimea.

The Chekur-Koyash deposit is situated on the southeastern coast of the Kerch peninsula, on the Kerch strait. The country consists of lagoonal Upper Tertiary deposits (Miocene and Pliocene). The rocks dip gently N–NW, at an angle of 10 to 15 degrees, showing in places faults and folds. The deposit is located on the slope of a low ridge facing the sea. A N–SW section of this deposit across the slope shows the following sequence downwards:[18]

[16] Tikhonovich, N. N.: The Sukeievo deposit of oil and asphaltum in the Kazan government. The Petrol. and Oil-Shale Industr., n. 4/8, p. 50, 1920.

[17] The writer's personal observations.

[18] Mokrinski, V. V.: The Chekur-Koyash sulphur deposit. Reports K. E. P. S. Acad. of Sci. of the U. S. S. R., vol. 6, 1916.

	Thickness
Sarmathian clays	
Sands with *Spaniodontella*	20 m.
Clays and marls with *Spaniodontella*	85 m.
Sulphur-bearing clays (ore-bearing)	60 cm.
Clays and marls with *Spaniodontella*	10 m.
Clays with *Spiralis*	10 m.

A considerable part of the section shows gypsum in the form of laminæ and crystals enclosed in clays. The sulphur-bearing horizon consists of alternating layers of clay and marl, gypsum and sand, and belongs to the Chokrak horizon of the second Mediterranean formation (Middle Miocene).[19] Its thickness varies from 35 cm. at the center to 2 m. on the periphery, averaging 60 cm., and is conformable with the enclosing rocks. The deposit is bordered on the SE and NW by two vertical faults trending NE, 450 m. apart. Beyond the limits of these faults sulphur so far has not been found. The ore of the Chekur-Koyash deposit consists mainly of interbedded laminæ (Fig. 12) of pure sulphur and dark, bituminous, marly clay. The laminæ vary in thickness up to 2–2½ cm. The laminæ are commonly of a considerable extent without varying in thickness, and may be lenticular in shape.

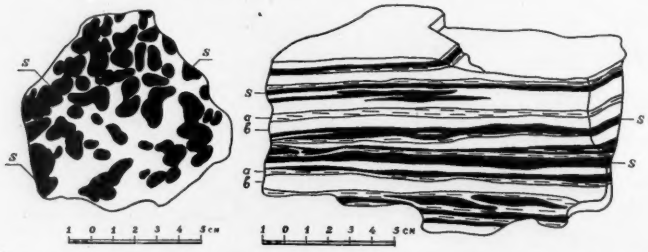


FIG. 12. Typical compact sulphur ore of the Chekur-Koyash deposit. Natural size. *S*, sulphur; *a*, dark bituminous clay; *b*, thin alternating laminæ of sulphur and dark bituminous marly clay.

FIG. 13. "Oölite" ore from Chekur-Koyash sulphur deposit. Natural size. White field, compact bluish-gray marl; black spots (*S*), sulphur.

[19] Luchitski, V. J., and Mokrinski, V. V.: Sulphur deposits of the Kerch peninsula. Mem. Crim. Soc. Nat., vol. 8, 1925. Much evidence is taken from this paper.

Sulphur laminations consist of pure, non-bituminous crystalline sulphur of light yellow color (unlike Knibyshev) with a structure resembling selenite. Laminæ of marly clay, colloidal in character, enclose numerous euhedral grains of calcite (up to 40%), grains of dolomite (15%) and rarely, small concretions of lutecite. In all of these deposits, Knibyshev, Sukeievo, Chekur-Koyash, chalcedony is lacking. May this not be of genetic significance?

At the west fault "oölite" ore occurs, which towards the center and downwards passes into laminated form. "Oölitic" ore is associated with dense marls with faint traces of sedimentation, but is traversed by irregular laminations of marly clay. Sulphur "oölites" are irregularly dispersed within the former as well as the latter rock. From the latter they are easily separated. Sulphur "oölites" consist of finely crystalline sulphur of pale yellow color, without admixed calcite. They are nearly spherical in shape, varying in diameter from 0.5 to 2 cm. In marls they are fairly compact, but in clay, they are loose and easily crushed. They show no concentric nor radial structure.

Under the microscope, marl also shows numerous euhedral grains of calcite (up to 70%), dolomite (6%) and inclusions of lutecite. Calcite shows close connection with lutecite, suggesting a simultaneous origin. Grains of calcite enclosed in lutecite and, inversely, areas of lutecite enclosed in the mass of calcite, are observed. In places, sulphur shows the same intimate association with calcite and lutecite.

Segregation of sulphur also occurs in the form of well developed crystals up to 5 cm. in length in cavities in the rock. They differ from the sulphur described above in their bright amber-yellow color. They are undoubtedly a product of recrystallization of primary sulphur, and are commonly accompanied by crystals of celestite, jarosite, and gypsum. In addition, large quantities of small water-transparent gypsum crystals with bright faces occur in cracks in the marls. In places, these crystals coat the surface of compact, finely crystalline sulphur.

At the surface, the sulphur-bearing layer loses sulphur and ac-

quires the brownish colors of iron hydroxides. At depth, considerable quantities of pyrite appear. The layer overlying the gray lamination consists of dense bluish-gray marl, and contains large quantities of gypsum. Sulphur occurs in it in small quantities, in the form of recrystallized, coarse-grained deep amber-yellow sulphur.

Associated with one of the faults at the Chekur-Koyash deposit is a sulphuretted hydrogen spring, and similar springs are numerous in the Kerch peninsula. Small quantities of flake-like sulphur are segregated in the beds. Deep in the rocks of the Chekur-Koyash deposit, sulphuretted hydrogen is also found.

Sulphur Deposits on the Slopes of the Kazbek Volcano in the Caucasus.

Quite different in structure from the sulphur deposits described above are those on the slopes of the volcanoes Elbruz, Kazbek, and Alaghez in the Caucasus,[20] and at Kamtchatka.[21] Whereas the sulphur deposits described above are bedded in sedimentary rocks and show no igneous connection, the deposits now under consideration are directly connected with volcanic processes. Such sulphur is epigenetic. It originated in one of the latest phases of cooling of the volcanic hearth, *i.e.* solfatara. Similar volcanoes are known in Japan,[22, 23] Java,[24] the Andes in Peru,[25] Chile and Italy; they occur in Kamtchatka (Okhotsk Sea) and in many other younger volcanic districts. Very curious processes connected with them are described by Kawasaki [23] and Inouye.[22]

On the northern slopes of the Kazbek volcano, near the pass of

[20] Moeller, V., and Denissov: Mineral deposits and waters of the Caucasus. Tiflis, 1917.

[21] Lavaritsky, A.: Avacho volcano and its state in 1931. Trans. Centr. Geol. and Prosp. Inst., fasc. 35, 1935.

[22] Inouye, J.: A peculiar process of sulphur deposition. Jour. of Geol., vol. 24, no. 8, 1916.

[23] Kawasaki, S.: Origin of formation of sulphur on Volcano Shirane Kozuke. Jour. of the Geol. Soc. of Tokyo, vol. 10, no. 122, 1930 (in Japanese).

[24] van Padang, M. Neumann: De Noordelijke doorbraak in den Papandajan Kratern. De Mijningenieur, 1929, 10. Abstr. N. Jahrb., 1930, II, 358.

[25] Ferron, R. D.: Sulphur in Peru. Eng. Min. Journ., Feb., 1934.

the Military Georgian Road, and west of it, in the Trusovski Pass (sources of the Terek) are situated several sulphur deposits.[26] Near the villages of Abano and Keterek, are cold sulphuric alkaline springs. Farther on toward the Military Georgian Road numerous ferrous carbon dioxide springs occur. The content of H_2S in the former reaches 87 per cent (volumetric). The sulphur deposits occur higher up. As suggested by Petrov,[26] part of the gas rises and oxidizes into sulphur and sulphuric acid. It may also be that sulphuretted hydrogen waters, partly oxidizing at the deposits, descend and reappear at the surface in the form of springs. South of the village of Ketersee, in the Terek floodplain, at the contact of flint with Jurassic clay schists, which are the most widely distributed rocks of the Caucasus, is a sulphur-alkaline spring. Above it, sulphur occurs along fine cracks and in cavities in clay schists. The schists, generally dark and compact, have been rendered colorless and friable. Under the microscope they show much fine-grained gypsum. In a coarse-grained scree that descends from the deposit, small crystals of gypsum occur in great quantity. The whole scree consists of the latter and of disintegrated schists. Moreover, gypsum is found in all the fissures with sulphur, apparently formed simultaneously with it. In rain-protected places are crusts and small radial aggregates of snow-white acicular crystals of hydrated aluminum sulphates.

Downstream from this deposit, near the village of Abano, is another analogous sulphur outcrop within the boundaries of the Terek terrace. Here sulphur plays the part of cement, and the flint is thoroughly impregnated with it. Part of the latter is friable and easily powdered; in other cases it is covered with a readily detachable disintegrated crust.

Two kilometers west of the village of Abano is the analogous deposit of Ketersee. The village of Ketersee is surrounded by numerous sulphur-alkaline springs. Upstream from the latter, the talus and remains of old workings are impregnated with sulphur. Here also gypsum, ceramohalite, and metamorphosed slate

[26] The description is given from the paper by V. P. Petrov: Materialien zür Erforsch, der Schwefellangerstätten in der Jrussowskij Schlucht. Jravaux de l'Inst. Pétrogr. de l'Acad. d. Sciences de l'U. R. S. S., livr. 3, 1932.

occur. The processes here are on a larger scale. It is to be noted that gravel covering the workings of 1896–1914 is cemented by sulphur.

The above evidence is in favor of a recent origin of sulphur.

Gumur Sulphur Deposit.[27]

The Gumur sulphur deposit is located 60 km. north of the city of Nakhitchevan (Little Caucasus), near the village of Gumur, on the slopes of the extinct volcano Salvorti.

In a stretch of 8 km. seven sulphur outcrops occur, situated along a break. The sulphur-bearing areas have no definite shape. Sulphur occurs in cracks and cavities, and impregnates the andesitic lavas of the Salvorti volcano and, in part, the conglomerates. Some of the outcrops are accompanied by siliceous tuffs. Andesites, impregnated with sulphur, bear all the traces of metamorphosis under the action of sulphuric waters, which alunitized and decolored them, and removed all basic elements (Ca, Mg, Fe, and others). The rock is now a porous, white, fragile kaolin-like mass with high content of SiO_2, and TiO_2, the latter up to 4 per cent. Pores in this mass are completely filled with sulphur. In places silica has been redeposited in the form of ferrous opal. Sulphur is everywhere accompanied by gypsum and secondary pyrite. This process is connected with ancient, sulphuretted hydrogen hot springs, now dry. Along the line mentioned above are numerous calcareous alkaline-sulphate carbon-dioxide springs with traces of sulphuretted hydrogen. Secondary processes of sulphur oxidation with formation of gypsum are also observed, particularly in conglomerates, where a kind of aureole is formed around sulphur. Gypsum crystals up to 3 cm., in the form of curved swallow-tails are found. Sulphur has been segregated in the form of well developed crystals in cavities and in compact fine-grained masses impregnating a porous opaline rock.

[27] From a personal statement by A. A. Florenski. A paper is in preparation.

Sulphur Deposits of Kamchatka.

Interesting data regarding the activity of the solfatara of the active volcano Avacha (Avachinskaia Sopke) in the Kamchatka peninsula are given by Zavaritsky.[28] Numerous active solfataras are located in the interior as well as on the outer wall of the crater, consisting chiefly of pyroxene andesites (lavas and pyroclastic material). Fumeroles on the outer surface of the crater, being more accessible, have been studied. They are associated with cracks. Among them are those with low temperature (about 90° C.), those with high temperature (190° to 350°) and intermediate fumeroles. The chemical composition of the gases is somewhat variable, but it may be noted that fumeroles with high temperature are characterized by a high content of HCl, H_2S and SO_2 and are poor in CO_2. In all cases, 80 to 96 per cent. of the gas (by weight) consists of steam. Small quantities of B, AS, Sb, Al, Fl, and noble gases occur. The temperature and chemical composition of the same fumerole (NE II) may vary in the course of 24 hours.

The fumeroles are surrounded by deposits of various salts, and rocks are strongly disintegrated and metamorphosed. The salt depositions are mainly alunogen, halotrichite-pickeringite, sulphides of Cu, Fe, Mg, sassoline, and sulphur. Andesitic lavas and pyroclastic material, which have been subjected to the emanations of fumeroles, are disintegrated into semi-loose masses of white or light-pink color. Along cracks in these rocks and in cavities, sulphur, gypsum, anhydride, and other sulphates are segregated. Thin crusts of marcasite are present. The rock is alunitized. Disintegration may be so advanced that only an amorphous mass of opal and kaolinic minerals (galloisite) remain. In cavities gypsum, anhydrite, alunite, and sulphur are recognizable. Anhydrite occurs in the form of small, well developed crystals embedded in fine-grained gypsum, in places merging into the latter. Rivulets of molten sulphur have been observed in places flowing out of fumeroles. Pseudomorphs of α-sulphur after

[28] Zavaritsky, A.: Avacha volcano and its state in 1931. Centr. Geol. and Prosp. Inst., Trans., fasc. 35, 1935.

β-sulphur occur with optical properties more characteristic of the latter. The water vapor, which is the main component of the emanations, is according to Zavaritski,[28] of meteoric origin and is not juvenile.

GENESIS OF BEDDED SULPHUR DEPOSITS.

Although the genesis of the latter three deposits described is in no doubt, that of the bedded deposits is not yet conclusively established. The first three of the above-described deposits belong in this group. There are 14 or 15 different viewpoints[29] as to this problem, which may be divided into two groups: syngenetic theories, and epigenetic theories. The first is that of sulphur deposited at the bottom of closed basins (lagoons, lakes, etc.), where the enclosing rocks were being deposited simultaneously, with participation of microörganisms. This is the syngenetic theory most generally held. The epigenetic theories are about 12 in number. They are all in agreement that sulphur was either formed or introduced into rocks after they had been deposited. Points common to both groups of theories and universally recognized are: (1) formation of sulphur during reduction of sulphates; (2) a two-stage reaction: in a reducing medium sulphate is reduced with separation of sulphuretted hydrogen; after which, in an oxidizing medium, sulphuretted hydrogen becomes oxidized with separation of sulphur. Some investigators attach no great importance to the reduction of sulphates, whereas all recognize the separation of sulphur by oxidation of sulphuretted hydrogen. The process of reduction of sulphates in a natural medium is also interpreted in different ways.

In order to clear up the problem presented in this paper, two points are to be settled: (1) does the reduction of sulphates occur with participation of living microörganisms or without them? (2) Are sulphur and enclosing rocks syngenetic or was sulphur formed later?

[29] Murzaiev, A.: A short review of the theories and some considerations of the genesis of bedded sulphur deposits.

1. Methods of Reduction of Sulphates.

The question as to how the reduction of sulphates occurs may be answered by experimental work. As is known, gypsum is reduced by coal at a temperature of about 700°. At low temperatures, this reaction does not take place.

(1) Allen, Greenshaw, and Johnson [30] tried to reduce iron sulphate by an aqueous solution of starch and glucose at 300° C. The results were negative. On reducing by bacterial action, the reaction took place. Sterilization of the test immediately stopped the reducing reaction.

(2) Bastin [31] tried to reduce calcium and copper sulphates at room temperature by coal, unrefined oil, and petroliferous shale. The experiment lasted 385 days and gave negative results. No traces of reduction of sulphates, or separation of carbonates could be noticed. In a supplementary trial they used marsh gas, hydrogen, and acetylene with a solution of zinc, copper, sodium, and calcium sulphates. The tests lasted from 60 to 112 days with negative results.

Kharitchkov [32] assayed 8 samples of 10% solution of Na_2SO_4 and one sample of 10% solution of $MgSO_4$. The first three, mixed with an equal quantity of kerosene, were kept for 6 months at a window, in open glasses. The following three samples (one with $MgSO_4$) were heated for 420 hours at 96° C. in an open vessel with an equal quantity of kerosene. Finally, the last three samples, mixed with benzine and sealed in a tube, were heated for 420 hours in a vapor bath at 96° C. As an indicator for H_2S, $CdCl_2$ was used. In the first case no traces of the reduction of sulphates were observed; in the second, the carbon-hydrogenic layer became slightly yellowish (formation of CdS); in the third, where the pressure was not less than 3 atmospheres, both fluids were quite transparent. Only a slight turbidity from the white residual of the colorless sulphate was observed.

[30] Allen, Greenshaw, and Johnson: The mineral sulphides of iron. Am. Jour. Sci., vol. 33, p. 171, 1912.

[31] Bastin, E. S.: The problem of the natural reducing of sulphates. Am. Assoc. Pet. Geol. Bull., vol. 10, p. 1276, 1926.

[32] Kharitchkov, C. V.: On "artificial" drilling water in bore-holes for oil. Oil Industry, no. 17, p. 19, 1913.

The same author [33] kept a concentrated solution of Na_2SO_4 with kerosene at ordinary temperature for 3 weeks, and at 90° C. for 4 to 8 hours a day for a fortnight. No traces of reduction were observable.

Kharitchkov is led to the conclusion [32] that reduction of sulphates inorganically is possible, but only at considerable temperatures and pressures.

Thiel [34] reduced iron and zinc sulphates by means of recent deposits such as peat, mud from lakes, and floodplain deposits. Part of the samples were sterilized and left for 14 months at room temperature in closed flasks. The process of reduction in unsterilized samples was more energetic than in sterile ones, where bacteria were destroyed. Thiel explains the reduction of sulphates in sterile samples by different causes, and finally concludes that the rôle of microörganisms in processes of sulphate reduction is important. Beyerinck [35] was the first to discover bacteria-reducing sulphates which he called *Spirillum desulfuricans*. He showed quantitatively how successfully the reduction proceeded in the presence of bacteria. The necessary conditions were the absence of oxygen, the presence of sulphates and organic matter, and a temperature from 12 to 14° C., the optimum being at about 25 to 30° C.

Van Delden [36] continued Beyerinck's experiments. The results of his experiments bearing on the reduction of sulphates are shown in his paper. One of his tables is shown below.

Similar experiments with qualitative computation were carried out by Baars [37] and Sturm,[38] which showed the high effectiveness of bacterial activity.

If in a lake of 3 km. in diameter, and a sulphurated hydrogen zone of 10 m. in depth, the process of sulphate reduction takes

[33] *Idem.* Content of sulphates in drilling water and their value as indices of oil and bitumen. Oil Industry, no. 10, p. 14, 1913.

[34] Thiel, G. A.: Experiments bearing on the biochemical reduction of sulphate waters. ECON. GEOL., vol. 25, pp. 242–250, 1930.

[35] Beyerinck, W. E.: Centralblatt für Bakteriologie, 2 Abt., Bd. 1, 1895.

[36] Van Delden, A.: Centralblatt für Bakteriologie, 2 Abt., Bd. 2, 1903.

[37] Baars, J. K.: Over sulfate reductie door Bakterien. Delft, 1930.

[38] Sturm, L. D.: Contribution to the study of microflora of sulphur-bearing rocks.

EXPERIMENTS WITH A MIXTURE OF CULTURES OF *Spirillum desulfuricans* AND *Microspira æstuarii*.

Composition of solution		Period, days	Quantity of H_2S in mgr.	Quantity reduced
I. Marine water	500.00 gr.	27	843	1964
K_2HPO_4	0.25			
Asparagin	0.50			
Natrium lactate	2.50			
Mud from lake Dollard				
II. Tap water	500.00 gr.	19	1030	2424
NaCl	15.00			
K_2HIO_4	0.25			
Asparagin	0.25			
Natrium lactate	5.00			
$MgSO_47H_2O$	4.00			

place in 100 days (in summer) under the ideal conditions of Van-Delden, taking into consideration the second case (see Van-Delden's table), the quantity of sulphur secured in the given lake will reach 407 tons, or 45 kg. per sq. m. of the lake bottom. The similarity to natural conditions by no means weakens the process, but in some cases even stimulates it (substituting well-water for distilled, and phosphorite for K_2HPO_4, etc.). The reduction of sulphates with carburetted hydrogen matter (methane, etc.) occurs, as is generally known, with great difficulty under the action of very strong oxidizers. Uklonski [39, 40] suggests the participation in these reactions of catalyzers (celestite, pyrite, jarosite, kieserite, etc.), but gives no ground for such suggestions. The above experimental data show that the reduction of sulphates with bacteria is considerably more energetic than that without the participation of bacteria. Bacteria are widely distributed on the earth's surface and at depth. Recent investigations give evidence that the area of their occurrence is widening and that their rôle in geochemical processes is increasing. Lipman [41] discovered them

[39] Uklonski, A. S.: Reconnaisance work for sulphur in Central Asia and Kirghizia during the second Five-year Period. Ac. Sci., 1934.

[40] Uklonski, A. S.: Sulphur deposit of Shor-Su. Collected papers "Problems of Sulphur Industry in the U. S. S. R." Leningrad, 1932.

[41] Lipman, C. B.: Discovery of living microörganisms in ancient rocks. Science, vol. 68, no. 1760, p. 262, 1928, and Jour. Bact., vol. 22.

at a considerable depth in coal deposits. Bastin [42] found them in petroleum with water as deep as 945 m., the temperature reaching 47° C. Gahl, Anderson,[43] and Guinsburg [44] also found an active living microflora in petroleum waters at different depths. Sturm [45] discovered desulphurizing bacteria in sulphur ores from Chekur-Koyash and Knibyshev deposits. In some samples she found that bacteria are considerably more prevalent in sulphur laminæ than in the enclosing bituminous dolomitic limestones of the same samples. These data show how widely bacteria are distributed. Consideration of their extremely rapid reproduction emphasizes the importance of the rôle of bacteria in geochemical processes. Vernadsky [46] cites a series of most striking examples, one, that according to Cohn [47] one bacterium produces in 4 or 5 days a progeny of 10^{36} individuals with a volume equal to that of an ocean.

The author has endeavored to point out that there is increasing evidence in support of the reduction of sulphate by bacteria in the laboratory as well as in nature, and that the conception of sulphate reduction in nature without participation of bacteria meets with serious objections.

It is worth mentioning, that in both cases it is recognized that sulphates are reduced by carbon. Hunt [48] and others accept Bischoff's scheme for the bacterial process $CaSO_4 + C = 2CO_2 + CaS$ etc. The studies of Nadson [49] and Baars,[37] however, show that reduction by hydrogen is also possible in *statu nascendi*.

[42] Bastin, E. S., and Greer, E.: Additional data of sulfate reducing bacteria in oils and waters of Illinois oil fields. Am. Assoc. Pet. Geol. Bull., Feb., 1930.

[43] Gahl, K., and Anderson, B.: Sulphate-reducing bacteria in California oil well waters. Centralbl. Bacter., Abt. A, vol. 73, p. 331, 1928.

[44] Guinsburg-Karaguicheva, J.: Problems of oil microbiology. Bull. d. la Soc. des Natur. de Moscou, sect. géol., vol. 11 (1), 1933.

[45] Sturm, L. D., and Simakova, T. L.: On microbiological investigation of samples of sulphur from deposits of the Crimea and Turkestan. C. R. Ac. Sci. U. S. S. R., 1928, p. 133.

[46] Vernadsky, V. J.: Papers on geochemistry.

[47] Cohn, F.: Die Pflanze, p. 450, 1897.

[48] Hunt, W. F.: The origin of the sulphur deposits of Sicily. Econ. Geol., vol. 10, pp. 543–579, 1915.

[49] Nadson, G. A.: Microörganisms as geological agents. St. Petersburg, 1903, p. 79. See also Sturm, L. D.

Is the Sulphur Syngenetic?

The purpose of the present paper is to acquaint the reader with the structures of two types of sulphur deposits. One consists of bedded, sedimentary deposits of which the genesis is not clear (Knibyshev, Sukeievo, and Chekur-Koyash), whereas the other consists of deposits that fill cracks (Kazbek, Gumur, Kamtchatka) and the sulphur is clearly epigenetic. As is seen from the descriptions, the structure of the first type is laminated, the laminæ of sulphur being parallel; sulphur inclusions are distributed along a line, a considerable distance apart. Laminæ of sulphur are always conformable with those of the enclosing rocks. The latter are always of lagoonal origin (dolomitic limestones and marls).

In the second type, sulphur has no regular distribution within the rock. It impregnates it along previously existing cracks, pores, etc. The kind of enclosing rock is of no importance; it may be tuff, igneous rock, conglomerate, clay, schist, or any other. Such structure is characteristic of volcanic areas of circulating H_2S waters or H_2S gas, that rise from depth. Of the same structure are deposits of oxidized sulphides. All of these are epigenetic. If the structure of the former, bedded deposits, is quite different from that of the latter, their genesis must be different too. Hence—the former deposits are syngenetic. This is confirmed at Közuke, Japan,[23] where sulphur is deposited in layers at the bottom of a lake and is formed by oxidation of volcanic H_2S. The structure of the ore is regularly laminated, as in the case of the bedded deposits described above, Chekur-Koyash in particular. This is an example of a syngenetic deposit of volcanic origin. The difference in the origin of the H_2S in this case is unimportant here; only the mode of deposition of sulphur in the rock is of importance. In addition, it is theoretically difficult to admit that H_2S could penetrate in sedimentary layers only along the bedding planes, avoiding vertical cracks and joint-planes.[50] Syngenetic sedimentary deposits are always conformable with the enclosing

[50] The syngenetic volcanic deposits are well described by Kato, T., Watanabe, T., and Nakamoto, A.: On the sulphur deposits associated with iron sulphide ore, found in the Quarternary Formation of Japan. Japan. Jour. Geol. and Geog., vol. 11, nos. 3–4, 1934.

rocks, whereas in epigenetic deposits the minerals fill all the cavities met on their way.

Sulphur deposits may be classified as follows:

A. Bedded deposits (syngenetic).

(1) in sedimentary rocks as a result of reduction of sulphates; (2) deposited in layers at the bottom of volcanic lakes, as a result of oxidation [22, 23] of volcanic H_2S.

B. Fissure deposits (epigenetic).

(1) in sedimentary and igneous rocks, sulphur filling cavities and cracks in various directions as a result of oxidation of H_2S that arose from depth; (2) as the result of oxidation of sulphide ores. Similar deposition.

The origin of the sulphur deposits in the "cap rock" of the salt-domes of Texas and Louisiana is still not clear. I am inclined to agree with Brown [51] that the "cap rock" is syngenetic with the enclosing rocks (mainly anhydrite) lifted from depth by the intruding mass of rock salt. Workable deposits, however, are secondary according to Brown, and formed as the result of redeposition and therefore of enrichment of primary sulphur.

This classification once more confirms the above contentions: bedded deposits are syngenetic, fissure deposits are epigenetic. In epigenetic deposits H_2S, oxidizing into sulphur and depositing it in cracks in the rocks, partly continues oxidizing into sulphuric acid which corrodes the rocks (see description of deposits). This should also be true of bedded sulphur deposits if they were of epigenetic origin—but it is not.

Some authors suggest that originally sulphur filled cracks in every direction in the sedimentary rock and later was removed from the vertical cracks by water, but that in the horizontal ones it remained. This interpretation seems improbable since sulphur in the vertical cracks of Knibyshev, Sukeievo, and Chekur-Koyash deposits is alone, whereas in horizontal fissures it is associated with calcite. Where vertical cracks cross sulphur-bearing horizons no solution of sulphur from the laminæ has been observed.

[51] Brown, L. S.: Cap-rock petrography. Am. Assoc. Pet. Geol. Bull., vol. 15, no. 5, 1931.

Other authors [15] suggest that in bedded deposits the sulphur was reduced, and immediately replaced gypsum, thus accounting for the shape of the deposit. It is generally known, however, that reduction of sulphates occurs in two media and in two stages—reduction of sulphate to H_2S and its oxidation in another oxidizing medium. H_2S, being a mobile compound, readily migrates. It is difficult, therefore, to believe that such a process could occur under natural conditions.

The writer has often observed inclusions and laminæ of gypsum at various depths in bituminous rocks, yet no replacement at the contact of gypsum with bitumen has been observable. Miropolski [15] observed such transitions in the Sukeievo deposit, yet only in rare cases and on selenite-like sulphur only. Such rare cases need confirmation. The writer thinks, therefore, that it is impossible to set forth a theory of the origin of a whole deposit or a series of deposits based upon such rare unconfirmed cases. If such be the origin, many cases of it should be observed and in numerous deposits. Selenite-like structure (Chekur-Koyash and others) may be characteristic of sulphur itself. Zavaritsky,[28] as mentioned above, observed a similar structure in cooling sulphur of the Kamtchatka deposits.

Ahlfeld,[52] Uklonski,[40] and others suggest that the genesis of sulphur is connected with oil-fields (petroleum waters). In this case, large sulphur deposits ought to occur in the district of Baku or Gronzy.

The connection between sulphur and petroleum, bitumen, gypsum, anhydrite, dolomite, marls, or salt—all constant associates of sulphur,—is different. They all are deposits of shallow water basins or lagoons, mostly in coastal regions, and therefore occur jointly.

The same authors point to the occurrence of sulphur deposits in the south of the U. S. S. R. where Tertiary lagoonal deposits are common, whereas in the north they are absent or scarce. Vernadsky [53] points to the occurrence of bedded sulphur deposits

[52] Ahlfeld, F.: Ueber die Bildung von Schwefellagerstätten. Chemie der Erde. Bd. 8, H. 4, 1934.

[53] Vernadsky, V. J.: History of minerals of the Earth's crust, vol. 1, no. 2, Leningrad, 1927.

in younger Tertiary deposits. Permian sulphur formations are the oldest known. According to the syngenetic theory, however, sulphur is an associate of the warm climate of the period in which it was deposited, and not of the following one. It may be that the older the deposit and colder the climate, the poorer are sulphur deposits formed at the present time. A classification of bedded sulphur deposits according to their age gives three groups:

(1) Permian: Knibyshev, Sukeievo.

(2) Upper Jurassic: Persia, Caucasus, Central Asia (Titonian).

(3) Tertiary: Sicily, Cheruk-Koyash (Crimea), Sgor-Su, Ghezyn-Bulak (Central Asia), Roumania, Calabria, Marches, Radoboj, Croatia, Galicy, Upper Silesia, Swoszowice, Kokoschütz, etc. (Middle Miocene, Pliocene, Paleogene)

The largest number of sulphur deposits belongs in the Tertiary. Vernadsky [53] points out the absence of older sulphur deposits, which he explains by the chemical activity of sulphur which would cause it to migrate during metamorphism, or to enter into chemical combinations.

The Pemian sulphur deposits of the U. S. S. R. show very faint metamorphism as well as tectonic dislocations. This may explain why sulphur-bearing deposits are still preserved there. Further mention of other characters of the deposits such as their lagoonal origin as for example the laminated structure of deposits in sedimentary rocks, is unnecessary. They are sufficiently well shown in a series of papers dealing with this problem.[46, 48, 53, 54, 55]

CONCLUSIONS.

The above is intended to show: (1) that the reduction of sulphates under natural conditions most probably occurs biochemically; (2) that the sulphur of beddel deposits is syngenetic. The latter statement needs further investigation inasmuch as the process of diagenesis of sediments is not clear, in particular of

[54] Stutzer, O.: The origin of sulphur deposits. ECON. GEOL., vol. 7, pp. 732–743, 1912.

[55] Drobyshev, D.: Contribution to the problem of genesis of sulphur deposits in Daghestan highlands. Matériaux pour la geologie gen. et appl. Fasc. 182, Leningrad, 1930.

a calcareous mixture with sulphur which later turns into dolomite or marl with laminations of sulphur. Hunt's suggestions [48] with regard to the formation in lakes of calcium polysulphides, and block precipitation of sulphur upon their decomposition are of great interest, yet they need confirmation. It may be that those concretions of rounded or lenticular shape observed at Knibyshev and other deposits represent former flakes of gelatinous sulphur with calcite inclusions, which might be formed during water motion (under the action of wind, etc.).

It would be of interest to carry on bacteriological experiments and create in a laboratory an artificial "lake" with two zones, the upper, oxidizing, and the lower, reducing. The environmental conditions ought to be as near as possible to natural conditions in order to study the conditions of sulphur precipitation.

In studies of sulphur deposits secondary processes have not received much consideration. Sulphur is a chemically active element, it readily enters into reactions, it goes into solution and it sublimizes at 60° C. At a depth of 10 to 50 m. it is probably also susceptible to sublimation. If so, its vapor being heavier than air, it would migrate downwards. As soon as a sulphur layer is submitted to the action of water, or a cavity is formed around it, sulphur begins to alter, recrystallize, or migrate. I have observed it under such conditions. Finely crystalline laminæ of sulphur with calcite that exhibit no noticeable traces of secondary action may be a result of crystallization *in situ* by means of rearrangement of molecules of primary "flake"-like sulphur.

LENINGRAD, U. S. S. R.,
December, 1936.

EDITORIAL

THE ANNOTATED BIBLIOGRAPHY.

FEW of our readers, judging from the subscription lists, fully realize the present status and the advantages of the *Annotated Bibliography of Economic Geology.*

For long, geologists had been conscious of their disadvantage in not having at hand a current index or bibliography of world literature dealing with geology. This was particularly felt by economic geologists who perhaps were likely to have to start off on short notice to investigate regions unknown to them, or who might suddenly find themselves immersed in an investigation of some mineral substance regarding which they desired immediate knowledge of what had already been written. And particularly, the research investigator fretted at the time-consuming laborious process of trying to learn what, if anything, had been written about the subject in which he was interested.

This was the status in 1921 when a committee of the Society of Economic Geologists under D. F. Hewett worked out preliminary plans and cost estimates for a suggested index or bibliography. Later, Waldemar Lindgren, as chairman of the Division of Geology of the National Research Council, carried the work to a conclusion and organized the present *Annotated Bibliography of Economic Geology.* He not only championed it, but by his tireless efforts he personally raised sufficient funds to ensure the preparation of the manuscripts for eight years; he gathered together a coöperative corps of able abstractors, each an authority in his own field; and he persuaded the Economic Geology Publishing Co. to take over the publishing and distribution of it at their expense. But his efforts did not stop there. He himself, continued as its active head and the eight volumes that have now appeared constitute another great tribute to his foresight and

leadership. The enthusiasm he induced in the collaborators is exceeded only by his own, and those who use the Bibliography will recall many a chuckle when they read pithy annotations signed "W. L."

Last July, the original funds for the preparation of the manuscripts, administered by the National Research Council, were exhausted. Prospective users of the Bibliography, however, will be glad to know that the sponsorship of this publication is now taken over by the Society of Economic Geologists in place of the National Research Council and funds for the continuation of the work have been provided by the Geological Society of America, the Society of Economic Geologists, the American Association of Petroleum Geologists, the Economic Geology Publishing Co., and some few oil companies, mining companies, and individuals. Some more financial help is still needed, however, to place the enterprise on a sound basis. This editorial is not meant to be an appeal for funds for the furtherance of the Bibliography, but incidentally we do know that any such contribution would be greatly welcomed by Professor Lindgren. With some more help continuance of the Bibliography is assured.

It is our opinion, and the small subscription list confirms the judgment, that the advantages of the Bibliography are not sufficiently realized by most economic geologists, whether they be teachers, investigators, consultants, or on the staffs of oil and mining companies. Everyone who subscribes to this JOURNAL should for his own benefit also be a subscriber to the Bibliography.[1] Those who do not know it miss something useful; they should at least try it out for themselves. Those who do know it are enthusiastic supporters; they should tell others. If it is considered worth while and is to continue, it should be supported.

Some geologists may think the Bibliography is of use only to the research worker, to whom it is indispensable, but what about the consulting geologist? He may be undertaking an examina-

[1] Those who wish to subscribe will find an advertisement in this JOURNAL or they can communicate with Prof. W. S. Bayley, Univ. of Illinois, Urbana, Ill.

tion of an old mine and desiring any hints thereon he looks in the July 1936 issue of the Bibliography and reads:

13. VARVILL, W. W. The examination of abandoned mines: Inst. Min. and Met. (371), 16 pp., Aug. 1935.

Useful hints to those engaged in the difficult task of advising as to the wisdom of opening an old mine. There are many things to be guarded against and many eventualities to consider. The reviewer would add advice not to underestimate the abilities of the old miners. They were rarely fools. Of all the reasons given for closing a mine, the most probable is seldom mentioned, that is, that the ore gave out. W. L.

(We might add that the abstractors advice is as cogent as the authors'.) Or, if the geologist may need information about beryllium he will find an annotation about it and the reference on page 303 of the same issue. But, the petroleum geologist may say, "That is very nice for the metalliferous geologist, but what about myself, should I desire information regarding new methods of correlating non-fossiliferous drillhole sludges." I might reply, "Look up, among others, item 735 in the Bibliography." It reads:

735. HAGERMAN, TOR. Nya granulometriska undersökningar i Argentina (new granulometric studies in A.): Geol. Fören. Stockholm, Förhandl. 57 (4); 682–687, Nov.–Dec. 1935.

Describes further development and application of the study of size and shape of quartz grains in correlating sandy sediments (comp. this bibl., Vol. VII (2), no 816). By plotting shape of grains, as defined by width to length proportion, against length, a distribution field characteristic of the sample is obtained in the diagram. In oil exploration work for the Argentine government, the method has been used with great advantage in the thick, non-fossiliferous, and monotonous Tertiary sediments of northern Argentina. P. G.

Should the petroleum geologist state, however, that he wishes information about the origin of petroleum or underground conditions or high gas pressures or drilling technique or oil estimation or gas in Alberta, or oil possibilities in Tunisia, the information is to be found under 449 annotations and under another 249 annotations on geophysics, in the same volume. And there is an index to help him also.

The above are merely a few random examples of the purposes the Bibliography serves. Similar examples could be given for areal geology described, for mineral production, metals, nonmetals, coal, water, soils, and engineering geology. The last volume contains 2617 titles, with annotations of from a few lines to a third of a page in length.

If you agree with us that the Bibliography is worth while we suggest that you yourself become a subscriber, that you tell your associates about it, and that you make sure your librarian receives it.

ALAN BATEMAN.

DISCUSSION AND COMMUNICATIONS

ASBESTOS DEPOSITS OF THETFORD DISTRICT, QUEBEC.

Sir:— What follows is an interpretation of a paper entitled "Asbestos Deposits of Thetford District, Quebec," by H. C. Cooke, that appeared recently in this Journal.[1]

That the paper is very clearly written and illuminates the subject is my sole excuse for suggesting that Mr. Cooke has failed to place the proper keystone to the arch of his argument. I assume that one reading this discussion has carefully read Mr. Cooke's paper and that it is before him. I shall, therefore, simply rewrite the conclusions to Mr. Cooke's paper, emphasizing my personal interpretations of what are admittedly moot questions.

I. Processes of thrust-faulting induced tensional strains (deformation) within the peridotite of the Thetford region, particularly localized near fault planes. (See excellent illustrations in Mr. Cooke's paper and statements by Mr. Cooke.)

Where strain developed beyond the elastic limit of the peridotite openings (veins) were formed (Paige). The time element is of major importance in thrust-faulting. Great breaks do not occur at once but progressively over a prolonged period, nor are the forces set in action by such faulting balanced immediately, but are adjusted slowly over a long period (Paige).

Mr. Cooke has shown that the pattern of the asbestos deposits is identical with the structural fault pattern, and has shown indisputably that tensional strains (deformation) developed on a grand scale and on a small scale.

[1] ECON. GEOL., vol. 31, pp. 355–376, 1936.

II. Serpentinization is a process widespread within the peridotite mass (Cooke).

III. The fault pattern is not everywhere a forerunner of asbestos deposits (Cooke), because openings did not continue to form at places where asbestos deposits are absent (Paige).

IV. Cooke admits the difficulties inherent in the hypothesis of growth of asbestos fiber against great pressure; and must recognize the inconsistency of utilizing this force to explain opening of fissures within a terrane wherein tensional stresses are dominant (Paige).

V. Mr. Cooke eliminates "replacement" and "open fissure filling" by presentation of cogent arguments.

VI. In my opinion, all the important phenomena of the asbestos veins, of which many examples are illustrated in Mr. Cooke's paper, and some of which are enumerated below, are explainable on the hypothesis that *gradual opening of fissures in response to tensional strain was accompanied by contemporaneous deposition of asbestos.* (*a*) The gradual opening of the vein was an adjustment to tensional strain carried out beyond the elastic limit of the peridotite; (*b*) expansion induced by serpentinization (if such exists) would be taken up in the increase of volume incident to adjustment to tensional strain in the affected block; (*c*) the relatively constant ratio of width of wall-rock alteration to width of vein would be a natural accompaniment of this process; (*d*) the prevailing narrow width of veins meets the requirements of a gradual widespread adjustment throughout the affected terrane; (*e*) pressure of growing crystals to which much objection has been raised may be eliminated; (f) the angle of crystal fiber to walls of veins would follow from differential movement of walls during formation of fiber, and likewise bending of fiber within veins; (*g*) where the terrane is faulted but devoid of asbestos, its absence may be explained by the absence of openings at these places.

SIDNEY PAIGE.

WASHINGTON, D. C.

REVIEWS

An Attempt at the Correlation of the Ancient Schistose Formations of Peninsular India. By Sir Lewis Fermor. Memoir Geol. Surv. of India, vol. 70, part I. Pp. 51; map 1. 1936.[1]

The memoir, part I of which is the subject of this review, is a comprehensive discussion on the Archæan rocks of India by Sir Lewis Fermor; the remaining parts are to appear during the next few years.

The most recent geological map of India appeared in 1931. No description of the geology of the country was published with the map; Sir Edwin Pascoe is now engaged in compiling such a description and this will appear at an early date as a Manual of the Geology of India. Some sixty per cent. of the area of the Peninsula is occupied by crystalline rocks and it is to be expected, perhaps, that these should receive a more detailed treatment than can be incorporated in a manual. It is such a treatment that Sir Lewis now contemplates.

There are two methods of attempting such a comprehensive work; one is to write the whole and revise it immediately before publication; the other is to publish it piecemeal as the parts are written, with a final appendix in which may be summarized all new material that has accumulated during the successive appearance of the different parts. Presumably Sir Lewis intends to follow the latter plan.

The investigation of metamorphic rocks is a specialist's life study. Sir Lewis is such a specialist and his seventeen years of field work included in thirty-three years of service in India renders him amongst those fitted to undertake such a work. Many geologists would prefer to see each section, in a treatise of this nature, from the pen of the authority or authorities in each particular area. Sir Lewis's plan of writing the whole himself at least eliminates the possibility of acrimonious discussion that is so likely to appear from the clashing of the diverse views of authorities.

Those of us who have worked on metamorphic rocks and have also visited areas of metamorphic rocks in other countries will appreciate something of the task which Sir Lewis has set himself for India. In this country we have had detailed mapping in widely separated areas, and attempts at correlation may be compared, perhaps, to attempts at correlating the rocks of the Lake Superior region with metamorphic

[1] Published with the permission of the Director of the Geological Survey of India.

rocks in the Alleghenies, the Black Hills and in the Rockies, or between Scotland, Scandinavia and Central Europe. Unfortunately, we are prone to think of a country as a geological entity, forgetting the vastness of a country like India and the great distances separating the mapped areas. Except in a few isolated regions, the geological map of India gives but a crude sketch of the Archæan rocks.

Detailed mapping on careful modern lines has been in progress for little more than twenty years; Sir Lewis makes the illuminating remark that "most of our memoirs on the geology of Southern India were written before the introduction of the microscopic study of rocks into India." However, in Rajputana, Dr. Heron's record of nearly thirty years of continuous mapping has resulted in the only satisfactorily completed areal unit in India. In other parts of India most of the work has been in progress continuously since the War. In the Central Provinces, Sir Lewis Fermor's party has done some fine detailed mapping over a comparatively small area. In Bihar and the adjacent Eastern States Agency a party, centered around Singhbhum, has covered a rather larger area in detail. Recently a survey party commenced work in Bastar State, which should clear up some of the problems of the charnockites and related rocks. Geological surveys in South India have gone on continuously, but no connected account has appeared in recent years. These facts will indicate the real paucity of connection between these isolated areas.

Sir Lewis recognizes all the difficulties and clearly enumerates them. One turns these first pages with something of awe for this brave attempt —there will be much of reverence if, on its conclusion, Sir Lewis has unrolled before us a convincing picture of any detailed correlation which he may make.

Part I is introductory in nature, its principal object being to discuss the several factors that may be concerned in correlation and to divide the country into provinces of a size suitable for description. One may note, at the commencement, that the memoir's title is not perhaps correct since the author intends to describe rocks beyond the Peninsula—in Ceylon, Burma and the Himalaya.

On page 5 Sir Lewis re-quotes his definition of the term Archæan made in 1909; the arguments surrounding the use of the term *eparchæan unconformity* form nothing more nor less than a vicious circle. Cut down to the root of the matter the true definition is found on page 14—"I have taken the presence of either granitic or pegmatitic intrusives as sufficient reason for referring the rocks into which they are intruded to the Archæan rather than the Puranas."

In the excellent discussion of the well known factors involved in correlation, Sir Lewis brings up again the question of crush-conglomerates. I think, from their recent work, several Mysore geologists will demur

at the statement: "In the Dharwar series of Mysore there are many conglomerates, but these are all regarded by the Mysore geologists as probably due to crush." Except in Sir Lewis's own area, Central Provinces, this mode of origin for sheared conglomerates seems to have died, leaving no regrets.

Apparently the author intends to make some use of the manganese occurrences in correlation. This is dangerous ground of which, no doubt, he is well aware. In the Iron-ore series there is a manganiferous shale horizon near the base and another near the top. Similarly in the use of the iron-ores for the same purpose, although the Iron-ore series is the main source of iron-ores, the pebbles in the basal conglomerate indicate that iron-ores occurred in an older series.

There are several minor points with which some petrologists will not agree, such as metasomatism as an occasional factor in metamorphism, and the solvent action of water in metamorphism, but up to the discussion on charnockites there is nothing to cause serious disagreement from the point of view of the purpose of this memoir. Sir Lewis appears to have accepted Stillwell's view that the charnockites are metamorphic rocks of the hypo-zone. Many of us were of this view until recently, but some of us would now revert, in part, to Holland's original description of them as normal igneous rocks. May they not be rocks formed by the crystallisation of a dry magma at great depth? In discussing, on page 50, why the Cuddapahs never come in contact with the charnockites Sir Lewis gives two reasons. I suggest to him a third: the charnockites were intruded at such great depths that they were nowhere exposed at the surface up to the time of deposition of the Cuddapahs.

For the infra-plutonic zone the author has made a good case and many will agree to the probability of his eclogite shell. Its suggested influence in the causation of earthquakes is unconvincing.

Finally, Sir Lewis explains the manner in which he has divided India (unfortunately he heads his table "Peninsular India") into regions and provinces for purposes of description. The three regions: non-charnockitic, charnockitic and "extra-Peninsular provinces" give an unbalanced division so far as area is concerned, and especially so in that probably 95 per cent. of the work to date has been done in the non-charnockitic region. From the metamorphic point of view it is not a petrological division and gives neither a picture of facies nor of grade. It is simply a convenient description of areas, the charnockitic region covering merely the southernmost tip of the Peninsula and the east coast, the non-charnockitic being the rest of the Peninsula.

The eighteen subdivisions, or provinces, are on an areal basis but they are grouped into types some of which are, at least in name, lithological: in the non-charnockitic region there are the iron-ore provinces, the (man-

ganese-ore)-marble provinces and the igneous provinces; in the charnockitic region there are the iron-ore provinces, (manganese-ore)-marble provinces and the garnetiferous provinces; the extra-Peninsular provinces are grouped (naturally) into the Himalayan and Burma occurrences. The grouping contains elements of lithological types, elements of facies and elements of areal distribution—a real hotch potch! Several of the groups contain common characteristics. It might just as well have been left entirely areal. However, classifications of this nature are entirely for clarity in description, and I would not advise the reader to give to it, at this stage, any other significance.

In conclusion, I would suggest that as an appendix to the final part of the memoir the authorities on the different areas should be invited by Sir Lewis to express their opinions on his description of their respective areas and of his correlation, and so provide a completely balanced picture.

Correlations are undertaken by two types of people: those who are young and eager (I was rash enough to attempt one such some years ago) and those who, as they retire and leave the field to younger men, wish to leave behind them the fruits of their experience. Sir Lewis Fermor has left India; we wish him a long retirement and hope that he finds the time to put the finishing touches to his correlation.

J. A. DUNN.

GEOLOGICAL SURVEY OF INDIA,
CALCUTTA.

The Geology of Texas. Vol. II: Structural and Economic Geology. By E. H. SELLARDS AND C. L. BAKER. Univ. of Texas, Bull. 3401, Austin, Texas, 1934 (Distributed, 1936). Pp. 884, figs. 40, pl. 8. Cloth, 8vo. Price $3.00.

The first volume of the "Geology of Texas" dealt with the stratigraphy of the State. (See this journal, Vol. 29, p. 313.) The second volume discusses its major structural features and its economic mineral resources other than petroleum, the treatment of which is deferred to the third volume to be issued later.

The volume is divided into three parts, of which the first discusses the structural geology of the State east of the Pecos River (136 pages); the second the structural geology of Trans-Pecos Texas (98 pages), and the third the State's economic geology (653 pages).

The first part outlines the structural deformations affecting the State, followed by description of the structural features of the Gulf Coastal Plain, and those of Central Texas. The second part discusses the mountain-making epochs affecting the Trans-Pecos region, and its major structural provinces. In the discussion of structural geology the authors emphasize the fact that the structure of Texas cannot be understood

without a consideration of the structure of the neighboring States and Mexico. "A due sense of proportion compels one to admit that the mountain part of Trans-Pecos Texas is but a very small division, and a marginal one at that, of the southern mountainous wedge of the North American continent." "This wedge, being the narrowest part of the whole continent, is likewise the weakest and is the most highly deformed in later Cenozoic time after the partial collapse of the Mexican geosyncline and the possible disappearance by submergence of a former land mass lying off the present western and southwestern coast of Mexico" (p. 211). The explanation of the structural phenomena at present known is, according to Baker, "that brittle rocks at and near the surface, without superincumbent load of other rocks, have broken into a complicated mosaic of fault blocks by lateral slip movements in a zone under compression, producing elongated-domical or elliptical areas of uplifted ridges, the longer dimension or axes of which are nearly parallel to the direction of lateral slippage. Therefore, they may be a consequence of thrust or shear and differ from the commonly accepted thrust planes in that the fracturing is more nearly vertical than horizontal and the direction is more nearly parallel than at right angle to the direction of shear or thrust."

By far the greater part of the volume is devoted to an account of the present and potential economic resources of the State. It treats of the character of these resources and indicates where they exist. Many of them are now not used, but in these cases their possible uses are described and the manner of producing and utilizing them in other States are well outlined. Among these are asbestos, molding sands, graphite, volcanic ash, barite, and manganese ores. Many other minerals that are known to occur in small quantity are mentioned briefly.

The products dealt with at greatest lengths are clay, bentonite, coal and lignite, water-supplies, iron ores, mercury ores, silver ores, gypsum, sulphur and alkali salts. In each case the subject is covered very thoroughly.

Among the notable new contributions included in the volume is a study of the geology and character of the iron ores of East Texas by Eckel and Purcell, a preliminary report on the Terlingua quicksilver district by C. P. Ross, a preliminary report on silver-lead ores of the Shafter mining district by C. P. Ross and W. E. Cartwright, and an account of the Texas-New Mexico potash deposit by Mansfield and Lang.

The book contains a wealth of information on the mineral resources of the State. It is well edited and well printed and is a credit to the State Bureau of Economic Geology.

W. S. BAYLEY.

Some Magnetometric and Gravimetric Surveys in the Transvaal. By O. Weiss, D. T. Simpson, and G. L. Paver. Pp. 27; pl. 8. Dept. of Mines, Union of South Africa, Geol. Series. Bull. No. 7, 1936.

This short but interesting report covers test application of the magnetic and gravitational methods of prospecting to geologic problems in seven areas in South Africa:

1. Magnetic traverses across the Lower Witwatersrand System. Anomalies ranging between + and — 10,000 gammas, close relation between anomalies and geology was observed.

2. Torsion balance survey across the Doornkop Fault; a text book example of gradient and differential curvature anomaly.

3. Torsion balance survey across the Witpoortje Fault and Lower Witwatersrand beds; an example of anomalies which are easy to interpret if you know the geology.

4. Successful determination of the hade of the Witpoortje Fault by a magnetic survey.

5. Torsion balance survey for locating nickel ore pipes. Brilliant indication is given of the pipes in spite of a regional gradient of more than 50E.

6. A magnetic survey over Gossan, indicating the usability of magnetic methods in prospecting for nickel ore pipes.

7. Magnetic survey with negative results over chrome seams.

This is a valuable collection of cases of the application of these two methods.

Donald C. Barton.

Houston, Texas.

Rutley's Elements of Mineralogy. 23rd Ed. Revised and Enlarged by H. H. Read. Pp. viii + 490. Figs. 127. Thos. Murby & Company, London, 1936. Price 8s.

The popularity of this little book is indicated by the fact that it is its 23rd edition. It is practically a new book, 100 pages larger than the 22nd edition. The chapter on crystallography has been entirely rewritten. It has been increased in length from 40 to 74 pages and now contains all that is necessary to an elementary knowledge of the subject. That on the optical properties of minerals has likewise been enlarged from 16 to 43 pages. It treats in much greater detail than in earlier editions the theories underlying the phenomena, stressing throughout their practical aspects. The special part on the description of minerals is increased by 32 pages.

The method of classification is entirely new. It is a "combined economic and chemical classification directed to meeting the needs of the

beginner in economic geology." The plan is supposed to group the minerals "according to the useful element or group of elements contained in them," but unfortunately this grouping has made it necessary for the author to place all the silicates, except those used as ores of metals, with quartz and opal, presumably as ores of silicon, though it might be thought better from an economic point of view to class orthoclase and albite as sources of the alkalies. However, this anomaly is not serious in an elementary text. The silicates (except those worked for metals) are grouped together as the components of rocks. It seems unfortunate to the reviewer that the old chemical formulas for the silicates and some of the other complex compounds are employed instead of modern ones.

The descriptions of the individual minerals, while brief, are satisfactory. From them the student should get a good knowledge of their properties and be enabled to recognize them without difficulty.

On the whole the volume is one of the best elementary texts on the market.

W. S. BAYLEY.

Earthquakes. By N. H. HECK. Pp. 222, figs. 88. Princeton University Press, 1936. Price, $3.50.

A broad treatment by a member of the U. S. Coast and Geodetic Survey presenting a comprehensive picture of the subject rather than a specialized mathematical one. Seventeen chapter headings indicate the subject matter: Earth Vibrations, Effects of Tremors, Cause of Earthquakes, Release of Forces, Earthquake Study with and without Instruments, Present Status in U. S., Records and Interpretation, Location of Epicenters and Foci, Seismic Belts, Great Earthquakes, U. S. Earthquakes, Regional Investigations in Japan, Safe Construction, Summary of Earthquake Information, History of Seismology and References. Well written and illustrated; instructive and interesting.

Principles of Structural Geology. By C. M. NEVIN. 2d Edition. Pp. 348, figs. 163. John Wiley, 1936. Price, $3.50.

This edition follows the treatment of the first edition and is meant for preliminary students. It deals with physical properties of rocks, stress and strain relations, flexures, faults, joints, cleavage, mountain systems, topographic expression of structure and earth structure. A new chapter on Structures Associated with Igneous Intrusion (Cloos Method) by E. B. Mayo has been added, and previous misleading matter regarding the strain ellipsoid eliminated.

BOOKS RECEIVED.

J. D. BATEMAN.

Microscopic Structure and Concentratability of the Important Iron Ores of the U. S. S. R. B. COOKE. Pp. 121, pls. 46. U. S. Bur. Mines, Bull. 391. 1936. Price 20 cts. Excellent treatise of the mineralogy and microscopic identification of iron ore minerals; improved technique for polishing them, and concentration tests on U. S. iron ores.

Geology and Ground-Water Resources of Uvalde and Medina Counties, Texas. A. N. SAYRE. Pp. 146, pls. 11, figs. 3. U. S. Geol. Surv. W–S. P. 678, 1936. Price, 35 cts. General geology; ground-water occurrence; ground-water resources for irrigation; stratigraphy: Lower Cretaceous to Quarternary.

New York State Flood of July, 1935. HOLLISTER JOHNSON. Pp. 35, pls. 16, figs. 3. U. S. Geol. Surv. W–S. P. 773–E, 1936. Price, 15 cts. Record of intense rainfall, flood discharges, and storage.

Canadian Mineral Industry in 1935. Pp. 100. Can. Dept. of Mines, Mines Branch. No. 773, 1936. Price, 25 cts. Production of metals, industrial minerals, and fuels.

Mineral Industry of New Jersey for 1934. M. E. JOHNSON. Pp. 24, pls. 4. Dept. of Conser. and Develop., Bull. 43, 1936. Production statistics.

Richey-Lambert Coal Field, Montana. F. S. PARKER. Pp. 53, pls. 6, figs. 23, maps 2. U. S. Geol. Surv. Bull. 847–C, 1936. Price, 35 cts. Stratigraphy: Tertiary to Pleistocene; geomorphic history; Fort Union lignites.

Gold Deposits of the Virginia Piedmont. C. F. PARK, JR. Pp. 42, pls. 9, figs. 14. Va. Geol. Surv. Bull. 44, 1936. General geology; quartz, sericite, ankerite gold veins, and their secondary enrichment; description of properties.

Bauxite Deposits of the Gold Coast. W. G. G. COOPER. Pp. 35, pls. 10 (including maps). Gold Coast Geol. Surv. Bull. 7, 1936. Price, 3/–. Occurrence and origin by removal of silica, and solution and deposition of aluminum and iron.

Geology of the Monument Valley—Navajo Mountain Region, San Juan County, Utah. A. A. BAKER. Pp. 106, pls. 17, maps 2, figs. 3. U. S. Geol. Surv. Bull. 865, 1936. Price, 60 cts. Stratigraphy: Pennsylvanian to Quarternary include the Rico and Hermosa, oil-bearing formations; structure; geomorphology; oil occurrences. Fine block diagrams and remarkable photos of desert erosion forms.

Geology and Mineral Deposits of the Bay of Exploits Area, Newfoundland. G. R. HEYL. Pp. 66, pls. 7, figs. 8, map. Dept. of Nat. Res., Geol. Sect., Bull. 3. (Princeton Univ. Cont. No. 12), 1936. Stratigraphy, glacial and structural geology, petrology of basic intrusives, and granite batholith. Deposits of bismuth, pyrrhotite, antimony, arsenic, gold, copper, manganese, and iron.

Geology of the Southern Half of the Bay of Islands Igneous Complex, Newfoundland. J. R. COOPER. Pp. 62, pls. 7, figs. 14, map. Dept. of Nat. Res., Geol. Sect., Bull. 4 (Princeton Univ. Cont. No. 13), 1936. General geology; interesting structure of basic intrusives; detailed petrology of rocks of Bushveld type and their differentiation. Occurrences of chromite, asbestos, copper and copper-nickel sulphides.

The Stillwater Igneous Complex and Associated Occurrences of Nickel and Platinum Group Metals, Montana. A. L. HOWLAND, J. W. PEOPLES, AND EDWARD SAMPSON. Pp. 15, pl. 1. Mont. Bur. Mines and Geol., Misc. Contr. No. 7, 1936. A Princeton University study of the unusual "Little Bushveld" of Montana involving the origin of associated sulphides, nickel, chromite, and platinum.

Scenic Kansas. K. K. LANDES. Univ. of Kans. Bull., vol. 36, no. 18, 1936. A well illustrated descriptive booklet describing the scenic topographic features of the state.

Phosphate Rock Near Maxville, Philipsburg and Avon, Montana. J. T. PARDEE. Pp. 14, figs. 2, pls. 7, maps 5. U. S. Geol. Surv. Bull. 847–D, 1936. Price, 20 cts. Phosphate occurs in a folded stratum 12 to 16 feet thick in the Lower Permian.

Arizona Metal Production. M. J. ELSING AND R. E. S. HEINEMAN. Pp. 112. Ariz. Bur. Mines, Econ. Series 19, Bull. 140, 1936. Price, 25 cts. Statistical tables covering production of metals from 1858 to 1934.

Memoir on Fossils of the Late Pre-Cambrian from the Adelaide Series, S. Australia. SIR T. W. EDGEWORTH DAVID AND R. J. TELLYARD. Pp. 122, pls. 13. Roy. Soc. N. S. W., 1936. Price, 7/6. Descriptions and occurrence of unusual and interesting fossils.

Geology in the Coastal Atlas of Western Algeria. R. V. ANDERSON. Pp. 450, figs. 2, pls. 19. Geol. Soc. of Amer. Mem. 4, 1936. Monographic work covering geography, stratigraphy (Permian to Recent), coastal terraces, igneous rocks, structures and diastrophism. Excellent colored geologic map 24 × 38 inches; scale 1/200,000. Important work.

Tantalum, Niobium, Uranium, and Radium in Brazil. O. H. LEONARDOS. Pp. 56. Dept. of Mineral Production, Bull. 11, Rio de Janeiro, 1936.

SOCIETY OF ECONOMIC GEOLOGISTS

The annual meeting of the Society will be held jointly with the Mining Geology section of the American Institute of Mining and Metallurgical Engineers at the Engineering Societies Bldg., 27 West 39th St., New York City. The program follows:

Tuesday Night, February 16, 1937.

Annual Dinner and Meeting, Society of Economic Geologists: Harvard Club at 7 o'clock. Presidential Address: D. F. Hewett: The environment and relations of the hypogene manganese minerals.

Wednesday Morning, February 17, 1937.

Eugene Callaghan: Alunite deposits of Marysvale, Utah.

E. B. Eckel and F. W. Galbraith: Geology of the Neglected mine, La Plata District, Colorado.

H. V. Warren and J. M. Cummings: Textural relations in British Columbia gold ores.

H. C. Reed: Mineral deposits of Glacier Bay, Alaska.

F. G. Wells: Origin of the Bull Valley, Utah, iron ore deposits.

Taisia Stadnichenko: Types of coals.

Symposium: The geology of dam sites of the Tennessee Valley region:

1. E. C. Eckel: Disturbed and metamorphosed area to the east.
2. E. L. Spain, Jr.: Undisturbed sedimentary central section.
3. R. F. Rhoades: Lower western area of deep alluviation and faulting.

Wednesday Afternoon, February 17, 1937.

E. N. Patty: The airplane aids Alaskan mining.

T. S. Nolan and W. D. Johnston: Block diagrams in mining geology.

J. B. Stone: The structural environment of the Bendigo gold field.

F. C. Calkins: The Slumbering Hill, Nevada, region.

P. W. George: Geology of Buchans lead-zinc-copper-ore deposits, Nfd.

Y. S. Bonillas: Geology of the Taxco mining district, Guerrero, Mexico.

C. W. Vaupell: The Huitzuco mercury mines, Mexico.

B. S. Butler and E. D. Wilson: The Tombstone, Arizona, mining district.

Charles Spearman: Some major structural features of the Canadian Pre-Cambrian gold areas.

R. P. Fischer: The "sedimentary" deposits of copper, vanadium, uranium, and silver in the southwestern United States.

C. H. Behre, Jr.: New data on the Wisconsin lead-zinc district.

Symposium: The localization of ore bodies: E. L. Bruce: Geological relations of some major gold deposits of the Canadian shield.

SCIENTIFIC NOTES AND NEWS

O. E. Meinzer, retiring President of the Washington Academy of Sciences, delivered an address on "Our Water Supply" at the 275th meeting of the Academy, on January 21.

N. H. Darton, geologist, U. S. Geological Survey for nearly 51 years, has been retired at the end of a year's extension of his time. He expects to remain in Washington to complete work in progress and then to engage in private practice in geology of petroleum, underground waters and foundations. His collection of pamphlets, numbering 6000, from 1886 to 1936 is for sale.

Edward Wisser has resigned his position as chief geologist for the Cia. de Real del Monte y Pachuca, in Mexico, and is now in the Philippines where he may be addressed in care of the Calamba Sugar Estate, Manila.

A. I. Levorsen, consulting geologist of Tulsa, Oklahoma, and president of the Am. Assoc. of Pet. Geologists, 1935–36, gave a series of four lectures at the University of Kansas, December 14 to 17. The titles of the lectures were: Miscellaneous Problems in Petroleum Geology, Paleogeology, The Accumulation of Oil, and Petroleum Reserves and Discovery.

The Tennessee Division of Geology, which claims to be the oldest of the state geological surveys now in existence, founded 106 years ago, has moved to new quarters at 426 Sixth Ave., N., Nashville, Tenn. Walter F. Pond is the State Geologist.

W. H. Collins, director of the Canadian Geological Survey and acting director of the National Museum, died on January 14, at the age of 58.

A. H. Phillips, Blair professor emeritus of geology, Princeton University, died on January 20th, aged seventy years. He was a member of the Princeton faculty for 47 years, and a former president of the Mineralogical Society of America.

EMMONS MEMORIAL FELLOWSHIP.

The Emmons Memorial Fellowship in Economic Geology is available for this year (stipend $1,400). Applicants should be qualified by training and experience to investigate some problem in economic geology and should submit a definite statement of their problem to the Committee, under whose oversight the work will be undertaken at any institution approved by them. The Fellow must give his entire time to the problem, which may be used for a doctorate dissertation. Applications and accompanying testimonials should be submitted not later than March 1. Application blanks and further information may be obtained from Alan M. Bateman, Charles P. Berkey, Waldemar Lindgren, or the Secretary, Columbia University.

lemy of
ıe 275th

51 years,
e expects
o engage
ters and
om 1886

the Cia.
ilippines
Manila.
president
four lec-
es of the
, Paleo-
iscovery.
oldest of
ears ago,
e, Tenn.

ıd acting
ge of 58.
Univer-
er of the
neralogi-

available
training
logy and
ommittee,
tution ap-
problem,
and ac-
March 1.
rom Alan
Secretary,